ARMY RESEARCH LABORATORY

Bone Conduction Head Sensitivity Mapping: Bone Vibrator

by Maranda McBride, Tomasz R. Letowski, and Phuong K. Tran

ARL-TR-3556 **July 2005**

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Aberdeen Proving Ground, MD 21005-5425

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14. ABSTRACT

The military is interested in ways to incorporate radio communication in a multi-tasking environment. Bone conduction (BC) radio communication is an attractive means to communicate because it offers the ability to transmit and receive radio communication without compromising auditory awareness of the environment. Several companies are attempting to accommodate the needs of the military by creating communication devices that incorporate BC technologies. However, the effectiveness of these devices differs in many respects. One factor that affects the detectability of signals received via BC is the location of the BC transmitter (vibrator) on the head of the user. The intent of this study was to identify optimal locations for the placement of a BC vibrator, based on hearing threshold levels of various signals. Eleven signals were transmitted via bone conduction to 11 head locations of 12 volunteers. Results of the study indicate that the condyle (an articular prominence of a bone) is the most receptive location for a BC transducer because it generates the lowest overall threshold levels. Other sensitive and thus recommended locations include vertex, mastoid, and temple. The jaw angle location also resulted in relatively low threshold levels; however, it is difficult to maintain a stable position of the vibrator at this location, and therefore, this position is not recommended.

15. SUBJECT TERMS

auditory research; bone conduction; hearing threshold

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1. Introduction

Effective completion of military mission requires Soldiers to maintain auditory awareness of their environment, protect themselves from the hazardous effects of noise, and maintain two-way radio communication. Air conduction (AC) and bone conduction (BC) are two alternate audio interfaces for two-way radio communication. In the case of AC, the sounds are transmitted from a talker to a microphone and from a loudspeaker or an earphone to the listener's ear. With BC, sounds are transmitted through vibrations from the skull of the talker to a contact microphone and from a vibrator to the skull of the listener. In both cases, sound quality and intelligibility of transmitted speech depend on the technical parameters of the electro-acoustic transducers, their coupling with the users (talker and listener), and technical parameters of the transmission channel.

AC is the basic means of hearing and is much better understood than BC in terms of communication applications. Although BC is always induced by sound waves arriving at the head of the listener, its effectiveness is about 40 dB less than that of AC. Further, during BC, transmission sound waves at lower frequencies are impeded less than sound waves at higher frequencies; therefore, complex sound waves transmitted by BC may appear to be carrying less high frequency energy in comparison to air-conducted sounds (Newby, 1979). In order to compensate for these deficiencies, BC transmission requires the use of special contact microphones and vibrators directly coupled with and well matched to the skull of the user.

In military operations, BC communication may be a preferred means of radio communication over the traditional AC communication because it enables the Soldiers to hear verbal radio communications without eliminating their awareness of the acoustic environment. Such awareness is greatly compromised by the use of earphones or in-the-ear devices not equipped with a hearing restoration system. BC communication is also attractive because the transducers are lightweight, inconspicuous, and easily integrated into military headgear. These devices have proved their ability to provide necessary radio communication in quiet and high noise environments, especially when combined with an appropriate hearing protection system (Letowski et al., 2004, 2005). However, because of the issues described previously, it is imperative to determine the best coupling conditions for BC transducers used in military headgear in order to ensure that their use does not inhibit the safety and survivability of military personnel.

The effectiveness of BC communication greatly depends on where the transducers are placed on the head since skin thickness and bone structure varies between locations as well as between individuals (Studebaker, 1962). Although there have been some American National Standards Institute (ANSI) standards for BC hearing testing, they do not apply to the use of BC devices in military headgear. First, the physical design of BC devices used in military headgear does not conform to the design of the devices upon which the BC hearing standards are based. Standards such as ANSI S3.13-1987 and ANSI S3.43-1992 are based on vibrators with a specific circular

tip that protrudes slightly beyond the surface of the vibrator. Many of the vibrators incorporated into prototype communication headgear have a completely flat surface area and some are rectangular. Further, standardized testing methodology applies only to the BC transducers placed at the mastoid bone or forehead. Last but definitely not least, there are no standardized methods to measure static force applied to the vibrator.

The primary purpose of this research was to measure and compare the detectability of signals received via BC vibrators at different points on the listener's skull. Since the human head is a complex mechanical system with many modes of vibration and non-uniform mechanical properties, the location on the head to which signals are transmitted may affect how well listeners are able to detect and recognize the signals. The vibrator used in the study was comparable to the style of vibrator currently sought for military headgear. Since the detection of signals in a single ear was not of interest, masking and occlusion were not used in this study. Data obtained from this study will fill an important gap in our knowledge regarding head vibration patterns and will have immediate application for Future Force Warrior radio communication systems. The reported study is the first stage of the broader research program intended to determine the optimum number and locations of BC devices, both vibrators and contact microphones, for use in radio communication interfaces.

The main objective of the present study was to create a physical mapping of the head that identifies the pure tone detectability level of signals received via BC devices placed in various locations on the human head. The secondary objective was to compare these data with detectability data for several complex signals. The practical implications of this effort were to identify favorable and unfavorable contact points on the head for the placement of mechanical devices used to receive radio transmissions via bone conduction. The head mapping data will also be used in future studies to extend the understanding of the perception of simple and complex sounds via BC devices.

2. Method

2.1 Participants

Twelve participants between the ages of 18 and 42 participated in the study. All participants had normal hearing for pure-tone octave frequencies from 250 Hz through 8000 Hz (ANSI S3.6-1996) and hearing symmetry within 10 dB for all signals. The audiometric tests were conducted with an Interacoustics clinical audiometer AC40, Telephonics TDH-39 earphones, and a response button. Each listener was tested in a sound-treated booth that complied with ANSI S3.1-1999 requirements for hearing testing, and the audio equipment was calibrated before the testing. Participants were

not required to have experience in psychophysical studies. Demographic information was also collected from the participants.

2.2 Instrumentation

Following the hearing test, each participant was seated at the listening station. The listening station consisted of an Oticon[1] A20 BC vibrator, static force sensor, electronic voltmeter, headband, and a response push button (figure 1). The static force sensor was employed to measure and monitor the static force applied to the skull by the vibrator in order to maintain the repeatability of the mechanical excitation provided by the vibrator at various locations on the head. If the static force were allowed to vary considerably from one location to another, thresholds measured at various locations might not be comparable because of the differences in coupling the vibrator to the skull.

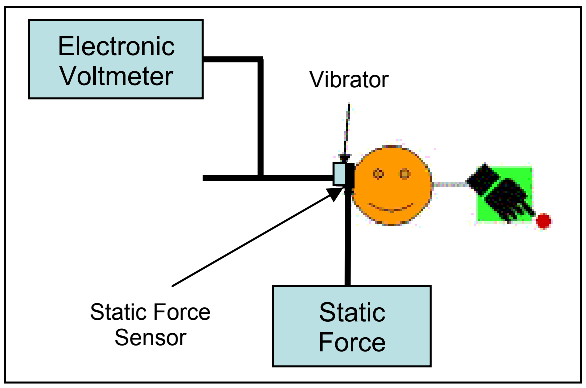

Figure 1. Block diagram of the instrumentation used in the study.

According to audiology-related literature, the static force applied by a bone vibrator to the human head must fall within the range of 2.5 newtons (N) (minimum force required for a stable position) and 5.9 N (the level of discomfort) in order to make a strong, yet comfortable coupling between the vibrator and the head. ANSI S3.43-1992, the standard used in the calibration of pure-tone BC audiometers, suggests a static force between 4.9 N and 5.9 N inclusively. However, this level of force is very uncomfortable for certain vibrator locations. Therefore, the target static force used in this study was between 3.9 N and 4.9 N inclusively for all vibrator locations and participants. This force range is identical to the force range recommended for coupling TDH[2]-39 earphones to the head during audiometric testing (ANSI S3.6-1991).

Pure-tone signals were generated with the same audiometer used to conduct the audiometric test (Interacoustics clinical audiometer AC40). Speech and white noise signals were generated on a personal computer via Sound Forge[3] 6.0 software. The computer was connected to the audiometer,

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[1]Oticon is a registered trademark of Oticon A/S.
[2]TDH stands for telephonics dynamic headphone.
[3]Sound Forge is a registered trademark of Sony.

which was used to adjust the signal level (in decibels [dB]) for all signals. Two pure-tone signals, 125 Hz and 250 Hz, were generated by computer because the audiometer was unable to generate a BC signal at the appropriate intensity levels for these frequencies. The orders of signal presentation and vibrator location were randomized between listeners.

2.3 Procedure

Each participant was asked to listen to incoming signals from the vibrator placed on his or her head and to respond by pressing the push button when the signal was heard. The incoming sounds were 125-, 250-, 500-, 1000-, 2000-, 4000-, and 8000-Hz pure tones, a burst of white noise, and three pre-recorded speech sounds ("aah," "eee," and "ooh"). An adjustable headband was used to hold the vibrator against the head, and the static force sensor was placed between the headband and the vibrator surface.

A reversed Hughson-Westlake procedure (Newby, 1979) was used to present test signals and to determine listeners' hearing thresholds for each signal-location combination. At the beginning of a test trial, the signal was set to a specific frequency and presented at a clearly audible (but not loud) sound level (e.g., 40 dB hearing level). The participant's task was to press the push button when s/he heard the signal. If the participant responded to the signal, the sound level was reduced by 10 dB. If the participant did not respond to the signal, the sound level was increased by 5 dB (ANSI S3.21-1997; Suter, 1993). This process was repeated several times until a signal level resulting in a 50% response rate was obtained for a given test signal. This marked the end of a trial. The procedure was repeated until hearing thresholds for all 11 signals and 11 locations were measured and recorded. Participants were able to take "stretch" breaks after every other vibrator location. See figure 2 for a flow chart of the experimental procedure.

2.4 Vibrator Locations

The vibrator locations used in this study were determined before experimentation and were the same for all participants. Figure 3 shows all the vibrator locations used in the study and the code names used for their identification. Some of the locations were chosen because they are common locations for BC vibrators and have been used before (i.e., the mastoid [G], forehead [C], and vertex [K]) (Frank, 1982; Richter and Brinkmann, 1981; Studebaker, 1962) or because they are being considered for use as bone conduction vibrator locations (A, B, F, and I). Others were chosen because they are commonly known electroencephalograph (EEG) electrode locations, making them easy to identify (D, E, H, and J).

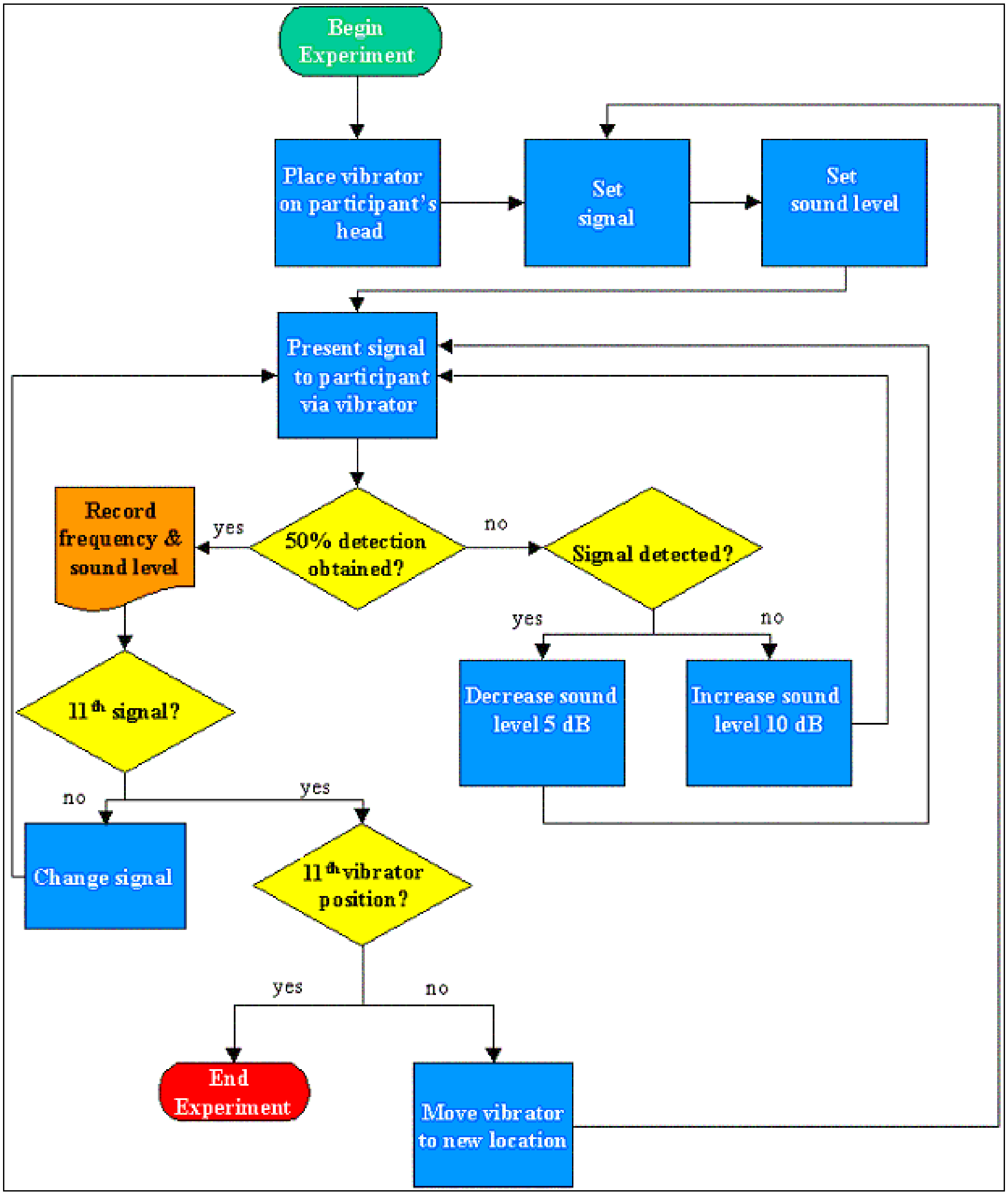

Figure 2. Experimental task flow chart.

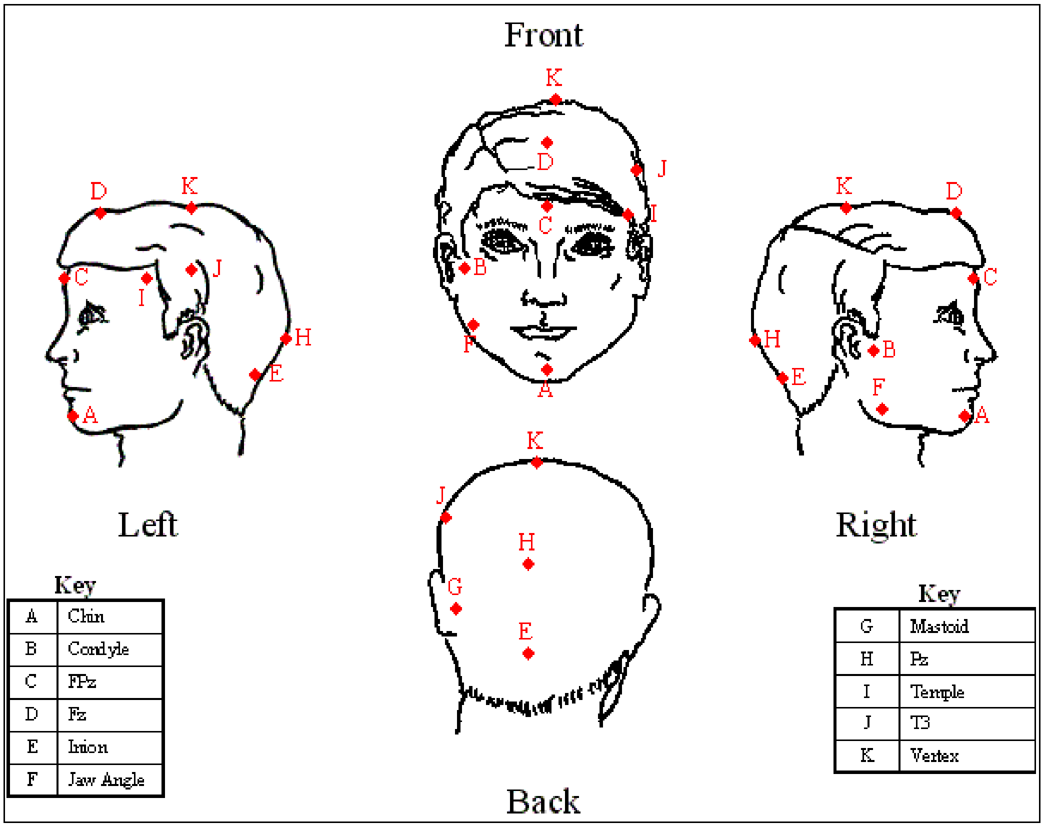

Figure 3. Vibrator locations.

3. Results

3.1 Experimental Results

All data collected in this study were subjected to basic statistical processing (means, variances, etc.) and exploratory data analyses (histograms, scatter plots, etc.). The two independent variables investigated in this study were (a) the type of sound (11 signals) and (b) the location of the vibrator (11 locations). The dependent variable was the hearing threshold level. Participants were treated as a random effects variable, and vibrator location, sound frequency, sound type, and sound level were treated as fixed effects variables. Effects were considered significant if the probability of difference because of chance was less than 0.05 ($p < 0.05$).

Participant means, standard deviations, minimum, and maximum values were calculated for each location-signal combination. Table 1 shows the means and standard deviations for each location per signal. The standard deviations ranged from 4.01 to 17.35 dB with an average value of 9.65 dB. Graphical representations of mean data are included in appendix A (location versus

signal) and appendix B (signal versus location). Appendix C provides graphical depictions of the average threshold at each of the locations on the human head for individual signals.

For each signal, the locations were sorted on the basis of their mean threshold value. The "best" contact point for a signal was defined as the location with the lowest threshold value. The locations were ranked so that the location with the lowest threshold value was at the top of the list (#1) and the one with the highest value was at the bottom of the list (#11). The rankings for each of the locations per signal are included in appendix D. The summary of the rankings per location is shown in table 2.

Table 1. BC hearing threshold means and standard deviations.

Location	125 Hz		250 Hz		500 Hz		1000 Hz		2000 Hz		4000 Hz		8000 Hz		aah		eee		ooh		white	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Chin	30.92	12.76	15.57	9.03	15.36	10.9	10.36	8.87	5.36	17.35	16	5.95	7.5	6.43	-12.5	8.93	0.857	5.16	0.143	6.3	3.93	4.87
Condyle	17.07	12.46	-1.64	5.64	2.14	8.16	-10.71	7.56	-5.71	12.07	2.22E-16	10.63	-10.36	7.96	-26.79	7.29	-19.29	4.32	-20.36	8.2	-17.86	4.69
FPz	32.07	16.05	17.14	9.94	14.57	10.71	7.14	10.32	3.93	16.98	14.64	13.22	-3.21	5.75	-11.43	5.49	-1.79	6.51	0.857	8.66	-0.714	8.05
Fz	28.64	14.48	14.5	10.51	9.64	10.39	2.86	11.55	-1.43	12.09	16.07	9.56	-3.93	4.01	-15	8.64	-8.21	6.62	-2.36	9.46	-5	6.5
Inion	29.36	12.97	14.36	11.46	17.5	10.03	5	8.09	5.36	13.57	13.93	9.8	2.14	6.71	-18.57	8.23	-6.07	7.89	-5.57	10.23	-6.07	8.36
Jaw Angle	17.93	13.57	-3.57	10.75	-1.67E-16	12.98	-7.86	9.55	3.21	14.78	8.21	8.82	-3.93	8.13	-20	10.41	-12.14	6.36	-16.43	10.75	-12.5	7.27
Mastoid	22.21	17.13	5.79	9.34	3.93	8.45	-0.714	10.16	-0.357	11.41	6.43	8.91	-16.79	5.41	-23.21	8.99	-13.21	7.5	-11.07	8.98	-11.79	6.39
Pz	34.21	14.38	19.86	5.5	19.86	11.02	7.86	12.36	1.43	15.35	15.71	13.65	-0.357	6.03	-13.57	7.6	-3.21	7.5	0	7.02	-0.357	6.03
Temple	26.5	14.73	10.43	11.91	10.71	11.34	3.21	10.85	-2.86	12.51	10.36	8.1	-5	6.2	-18.57	12.38	-8.93	6.96	-5.36	10.61	-8.93	8.81
T3	27.43	14.17	10.57	13.84	10	12.37	4.29	13.42	-1.43	14.28	14.64	9.46	-5.29	5.51	-17.5	11.29	-7.86	8.93	-3.79	11.96	-7.14	8.71
Vertex	22.57	14.82	2.93	10.96	1.11E-16	9.73	-5.71	11.24	-2.14	14.59	13.93	8.08	0	5.88	-23.57	6.33	-10	5.88	-12.5	6.19	-10.36	4.99

Table 2. Location rank tallies.

loc/rank	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th
Chin	0	0	0	0	0	0	0	0	3	4	4
Condyle	8	2	1	0	0	0	0	0	0	0	0
FPz	0	0	0	0	0	0	2	1	3	3	2
Fz	0	0	0	1	3	1	1	4	0	0	1
Inion	0	0	0	0	2	1	2	3	0	2	1
Jaw Angle	2	4	2	1	0	1	0	1	0	0	0
Mastoid	1	2	3	4	0	1	0	0	0	0	0
Pz	0	0	0	0	0	0	1	1	4	2	3
Temple	0	1	0	2	4	3	1	0	0	0	0
T3	0	0	1	0	1	4	4	1	0	0	0
Vertex	0	2	4	3	1	0	0	0	1	0	0

3.2 Symmetry Test

In the process of designing this study, the feasibility of testing symmetric locations on the head (e.g., right/left condyle, right/left jaw angle, right/left temple, etc.) was considered. However, such an approach would increase the number of test points and would greatly extend the duration of the study per listener. Therefore, to limit the number of test points, it was determined that there would be no need to test symmetric locations if the assumption could be made that there is no significant difference in the thresholds between points of symmetry. This assumption seems to be justified if the listeners have fairly symmetrical AC hearing. Thus, all the listeners participating in this study were screened for symmetrical AC hearing (see section 2.1). To verify the correctness of this assumption, one set of symmetric points (right and left mastoid) was also tested and analyzed.

Because the data spread of BC thresholds obtained in this study was not normally distributed (as indicated by the Anderson-Darling test statistic $p < 0.05$), a Mann-Whitney test was performed on the raw data to determine if there was a significant difference between the frequency thresholds at the two mastoid locations. The results of this test indicated that the threshold difference between these two locations was not statistically significant ($p = 0.1901$). Therefore, for the purpose of the study, it was assumed that mirror data points would have threshold values sufficiently close to those obtained at original measurement points.

4. Discussion

The thresholds obtained from this study were much lower than those obtained from clinical studies. This may be because the signals were presented by a reverse Hughson-Westlake procedure. Hirsh (1952) found that lower thresholds are usually obtained when the intensity of the signal goes from high to low rather than from low to high.

Based on the inspection of the graphs provided in appendix B, the threshold levels for the signals per location generally decreased as frequency increased; however, evidence of "notching" (or an elevated increase) was found at 4000 Hz for most locations. O'Neill, Frosh, and Jayaraj (2000) observed a similar phenomenon at 2000 Hz for a set of clinical data.

Based on the average thresholds for the 11 signals, the condyle appears to be the "best" contact point for BC vibrators. Of the 11 signals, the condyle was ranked number 1 for eight signals and either number 2 or 3 for the other three signals. The average ranking for the condyle placement was 1.4. The next best contact point was the mastoid with an average rank of 3.3.

The results of this study indicate that the condyle would be a good location to place BC vibrators. This location falls outside the helmet coverage area but is sufficiently close to be incorporated in headgear-supported BC interface designs. In addition, the condyle has the advantage of being close enough to the ear canal that any residual signal emanating from the vibrator because of acoustic leakage can be heard via AC. This may be an important practical consideration for low-power systems operating in quiet (stealth) environments.

Other locations with high rankings include the jaw angle, which primarily ranked first, second, or third, and the vertex, which was usually ranked second, third, or fourth. This indicates that all these locations are good candidates for vibrator location for radio communication purposes. The consistently poor performers included the chin, which never ranked better than ninth; Pz, which was ranked no higher than seventh; and FPz, which also was ranked no higher than seventh. Table 2 shows a tally of the number of times a location ranked first, second, third, etc.

The temple location used in this study was actually the location on the bone just above the temple; however, this proved to be a very difficult point for properly placing and securing a

vibrator. Moreover, it is a dangerous place for military applications since placing anything very close to the temple creates a health hazard. However, obtained data and informal comments made by the listeners indicate that the "temple location" may be a relatively effective location, especially if the transducer is placed a little bit higher than indicated on the head diagram. Thus, if the "temple location" is to be used in future studies, it needs to be considered as the place on the skull about 1 inch above the actual temple. Based on informal observations made by the listeners participating in this study, this may be a safer yet even more sensitive location than the specific temple location used in the study.

5. Conclusions

Based on the quantitative data and rankings, the "best" effective location for the BC vibrator used in radio communication headgear appears to be the condyle, followed by the mastoid and vertex. Although the jawbone ranked third, it was very difficult to hold the vibrator in place at this location. This complication would be intensified in situations when the person wearing the vibrator was expected to speak, thus having to move the jaw. Since the temple ranked fifth overall and had resulted in good informal feedback from the listeners, the "above-the-temple" location should also be considered in further studies.

In summary, the results of the study provide a basic sensitivity map of the human skull for directly transmitted vibrations. The condyle, mastoid, and vertex have been identified in this order as the most promising locations for vibration detection. A location on the side of the head about 1 inch above the temple may also be good. Future studies are needed to provide more definitive answers regarding the feasibility of using these locations with specific protective headgear and BC vibrators of various designs.

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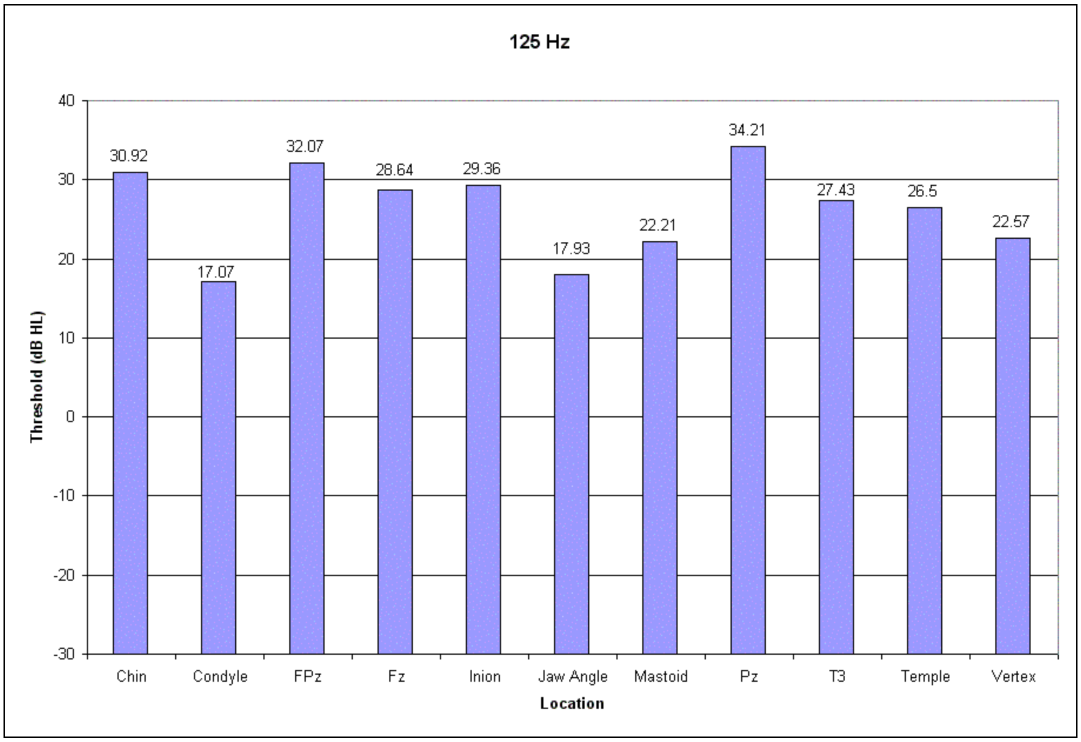
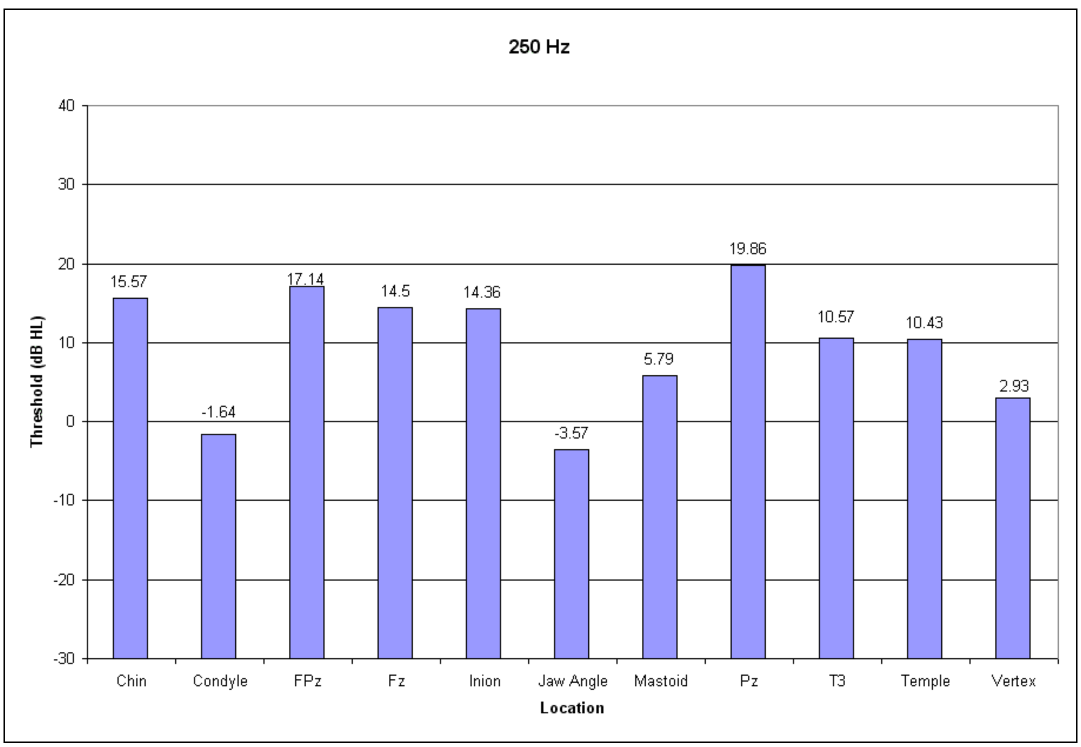
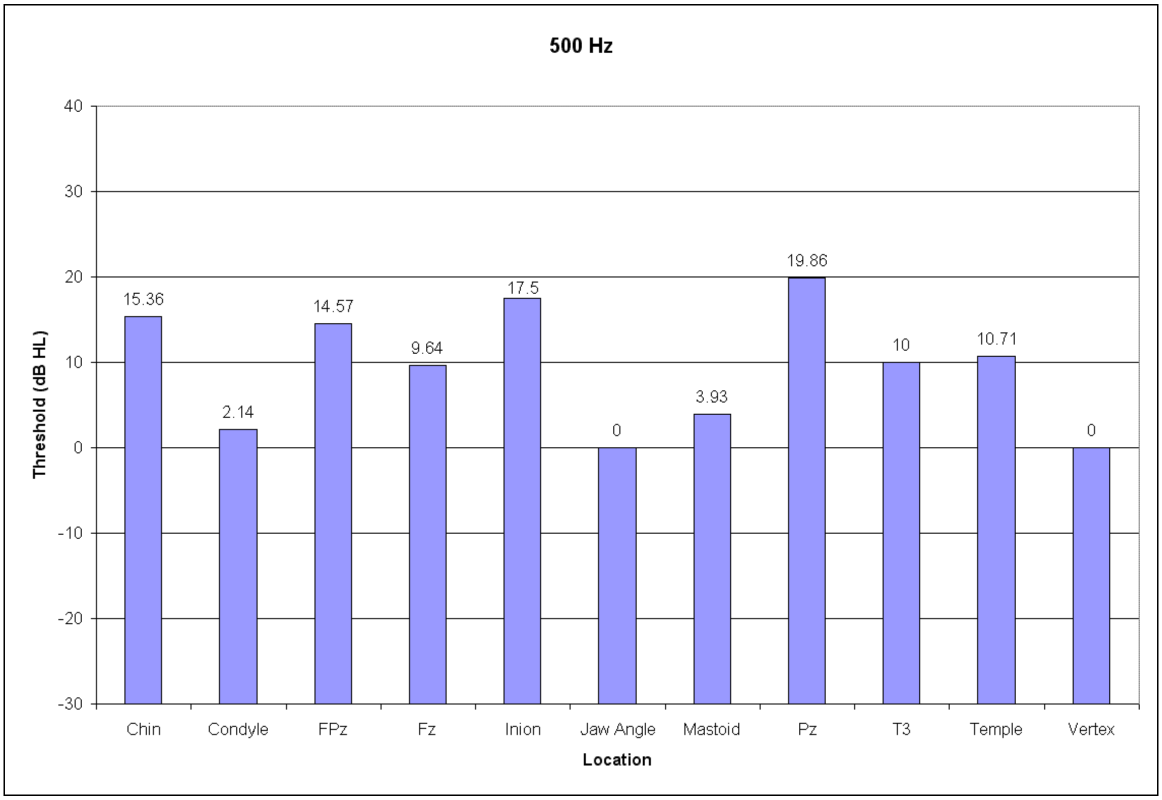
Appendix A. Arithmetic Means of BC Responses Per Signal



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30
20
10
0
-10
-20
-30
Threshold (dB HL)
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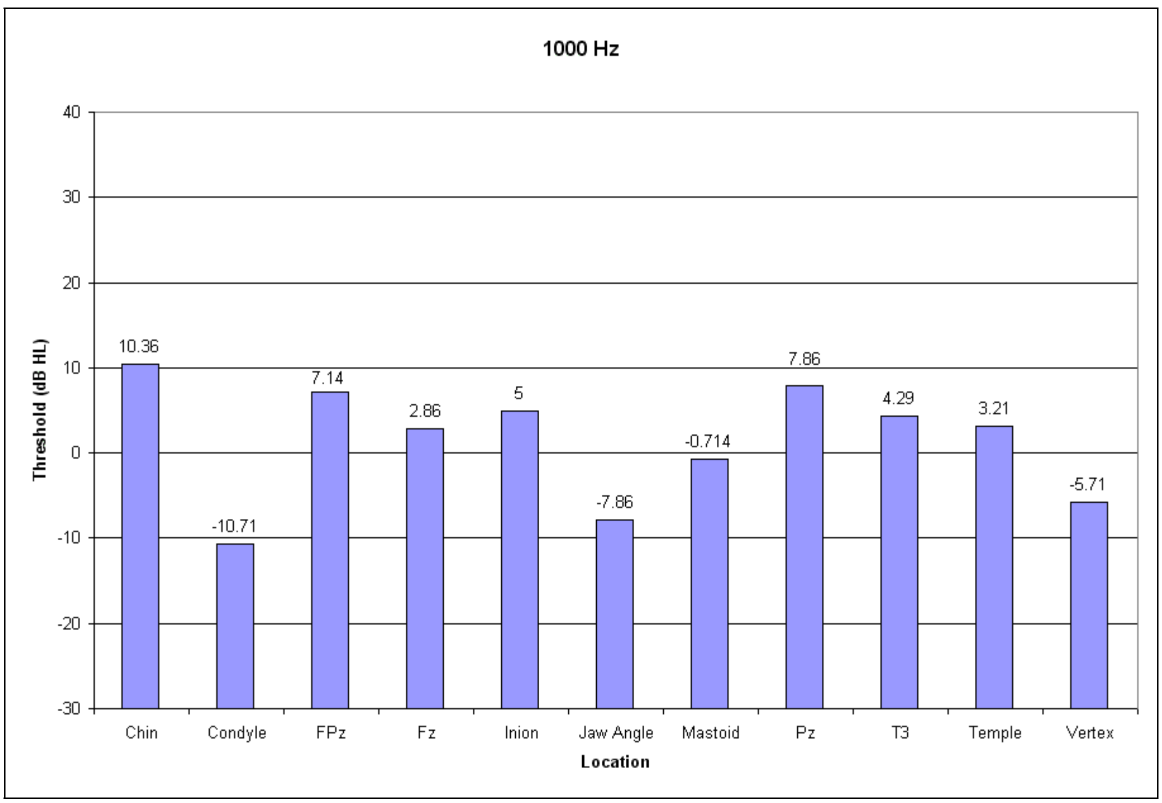
2.14
14.57
9.64
17.5
0
3.93
19.86
10
10.71
0
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location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20
10
0
-10
-20
-30
Threshold (dB HL)
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5
-7.86
-0.714
7.86
4.29
3.21
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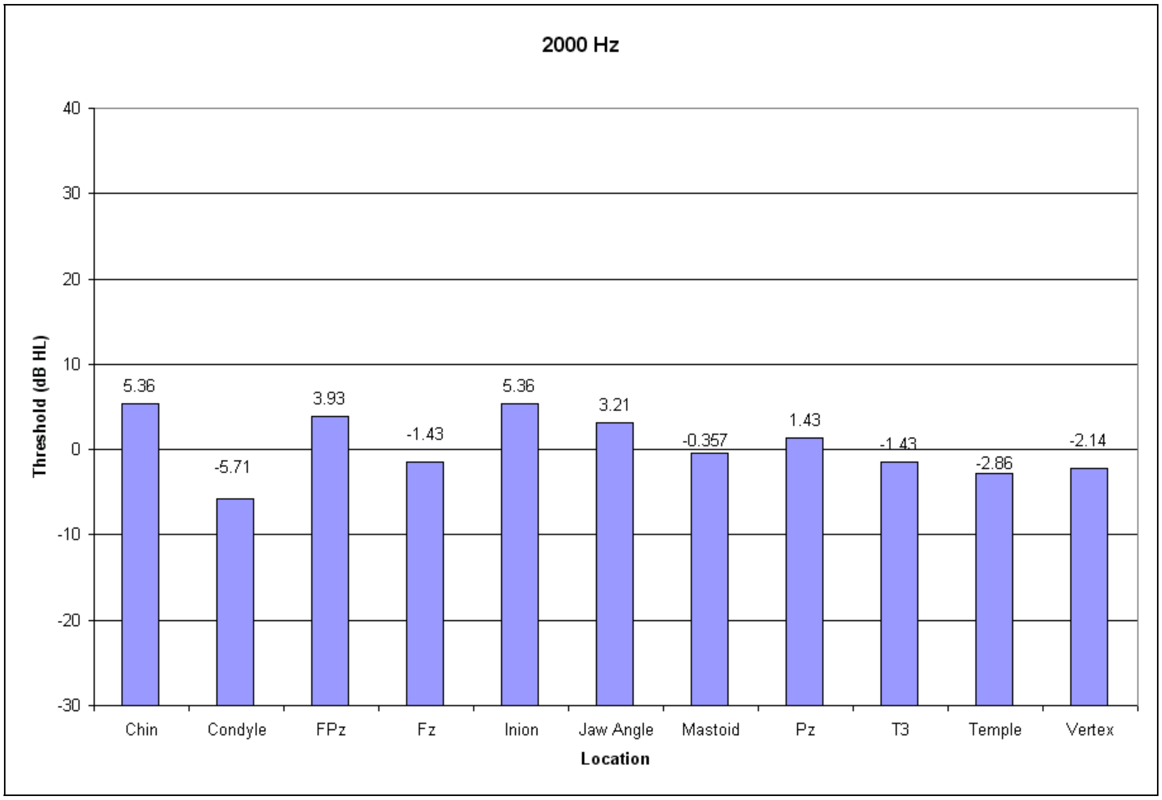
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location


2000 Hz
Threshold (dB HL)
40
30
20
10
0
-10
-20
-30
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3.21
-0.357
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-2.86
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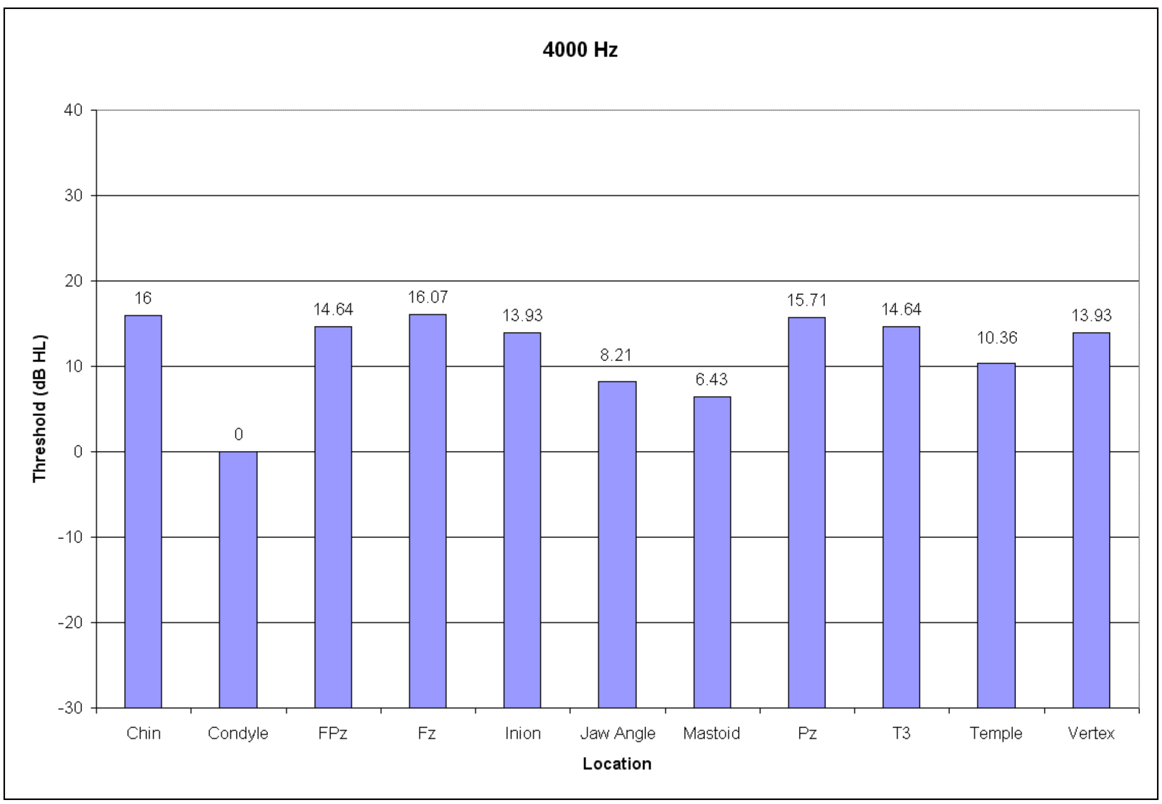
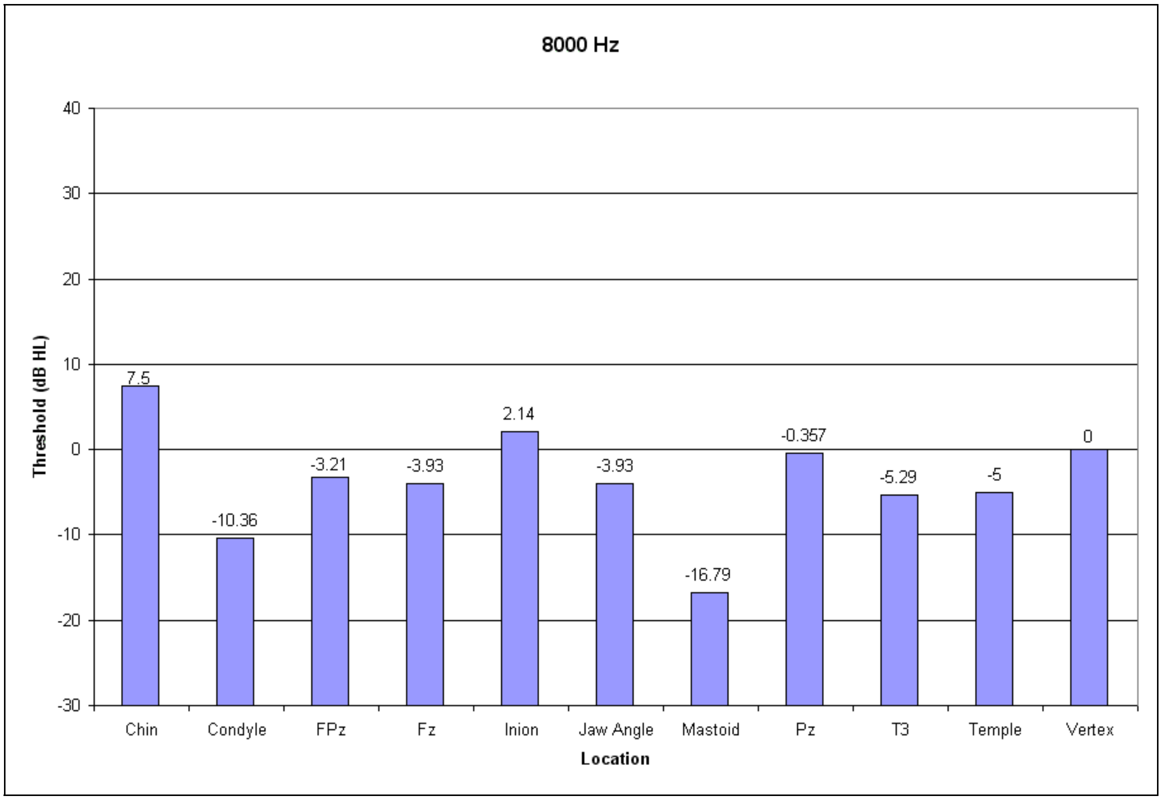
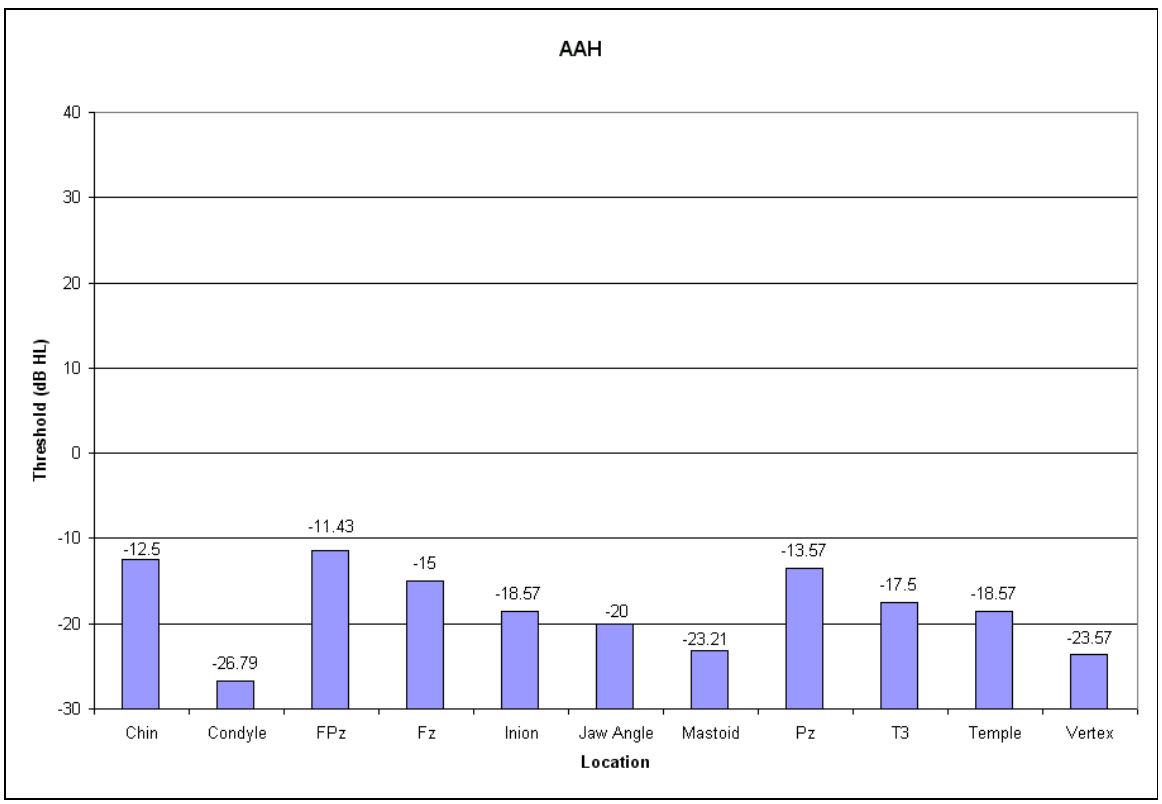
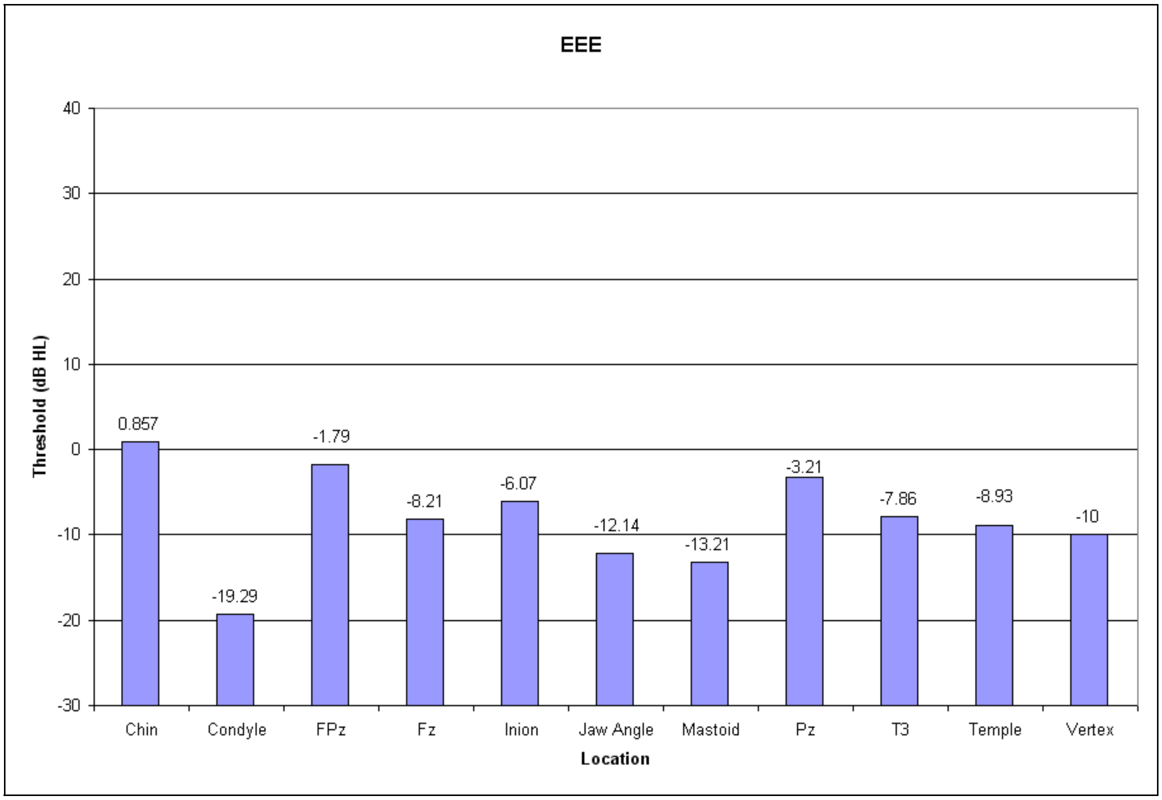
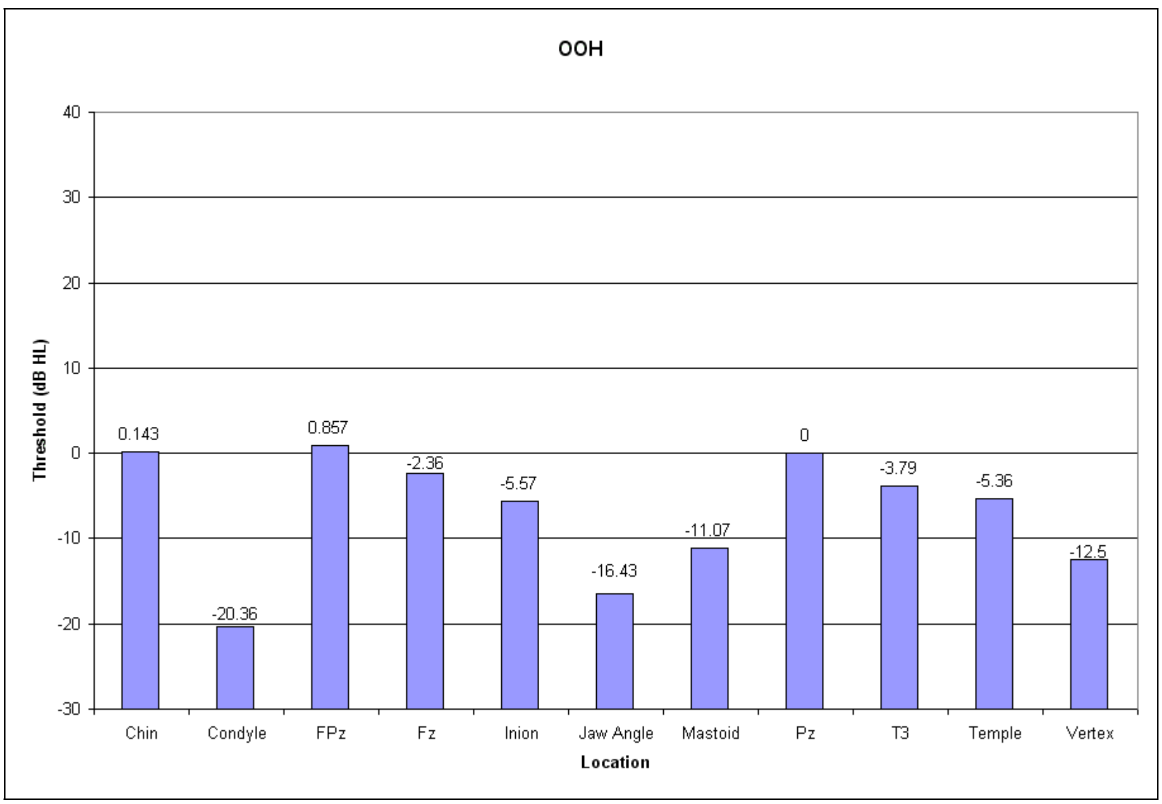
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location

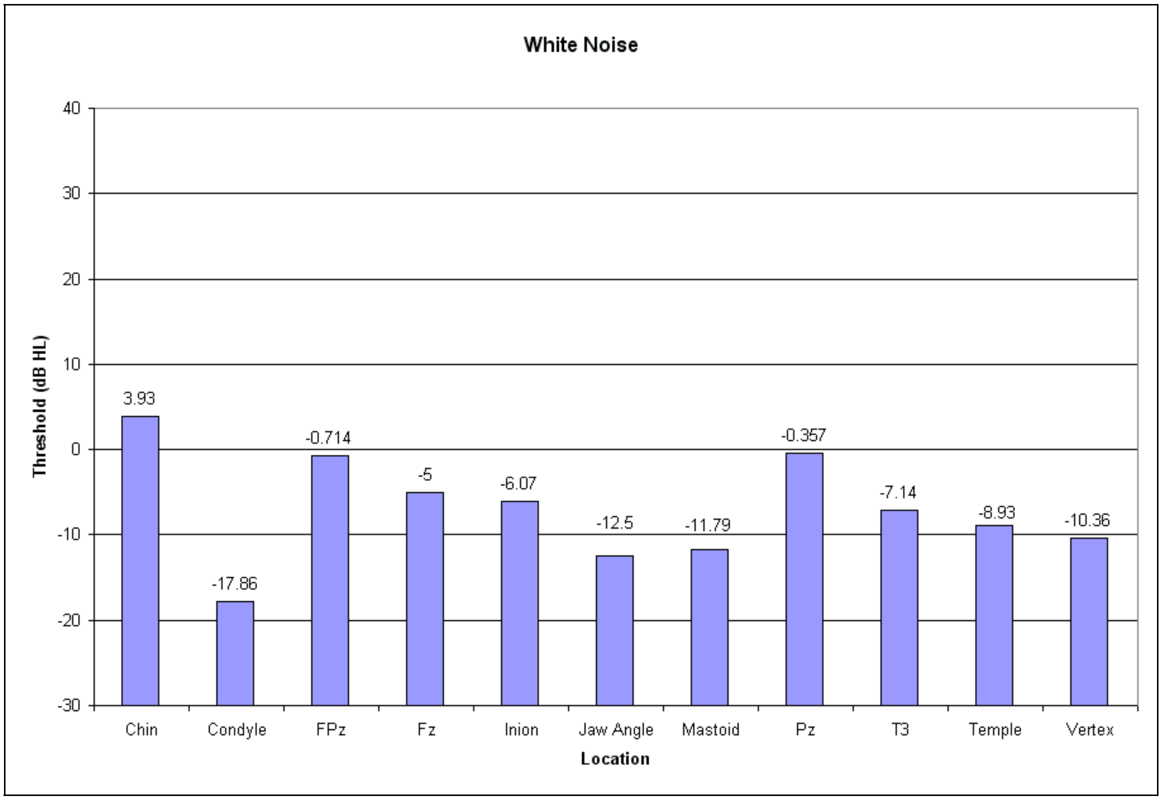

4000 Hz
Threshold (dB HL)
40
30
20
10
0
-10
-20
-30
16
0
14.64
16.07
13.93
8.21
6.43
15.71
14.64
10.36
13.93
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location

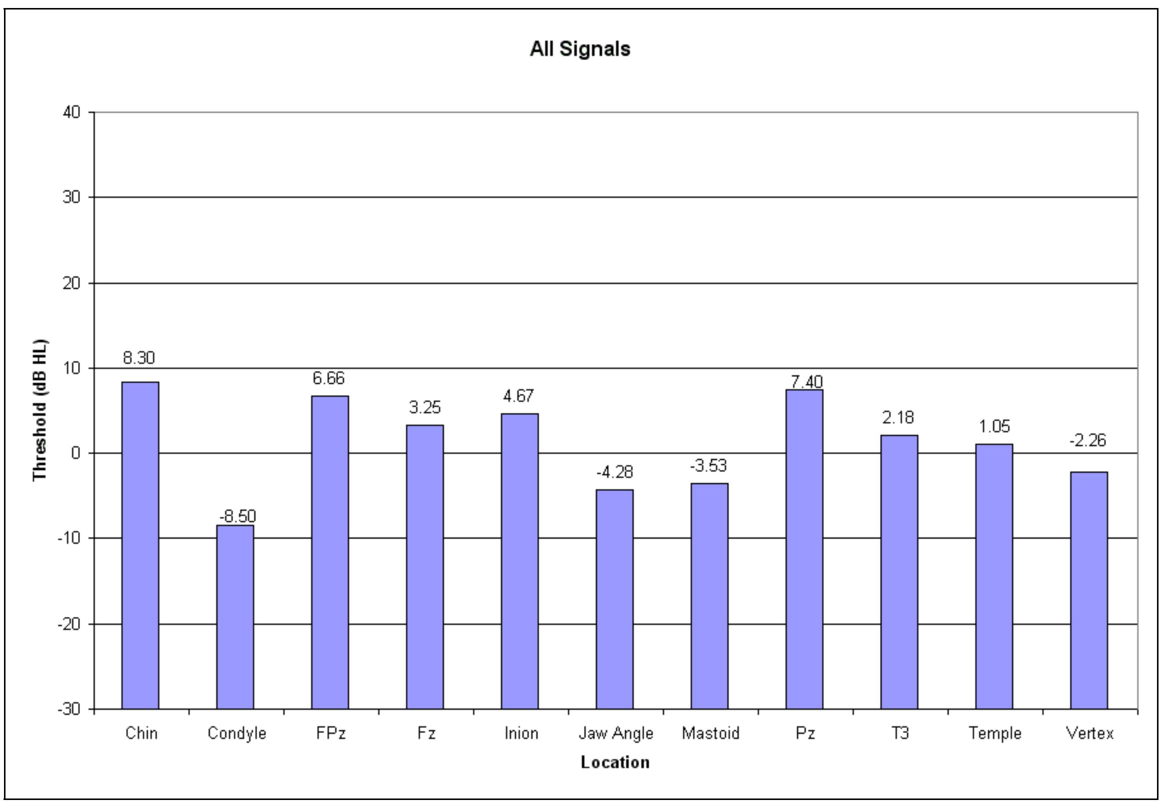

8000 Hz
Threshold (dB HL)
40
30
20
10
0
-10
-20
-30
7.5
-10.36
-3.21
-3.93
2.14
-3.93
-16.79
-0.357
-5.29
-5
0
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location


AAH
Threshold (dB HL)
40
30
20
10
0
-10
-20
-30
-12.5
-26.79
-11.43
-15
-18.57
-20
-23.21
-13.57
-17.5
-18.57
-23.57
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location

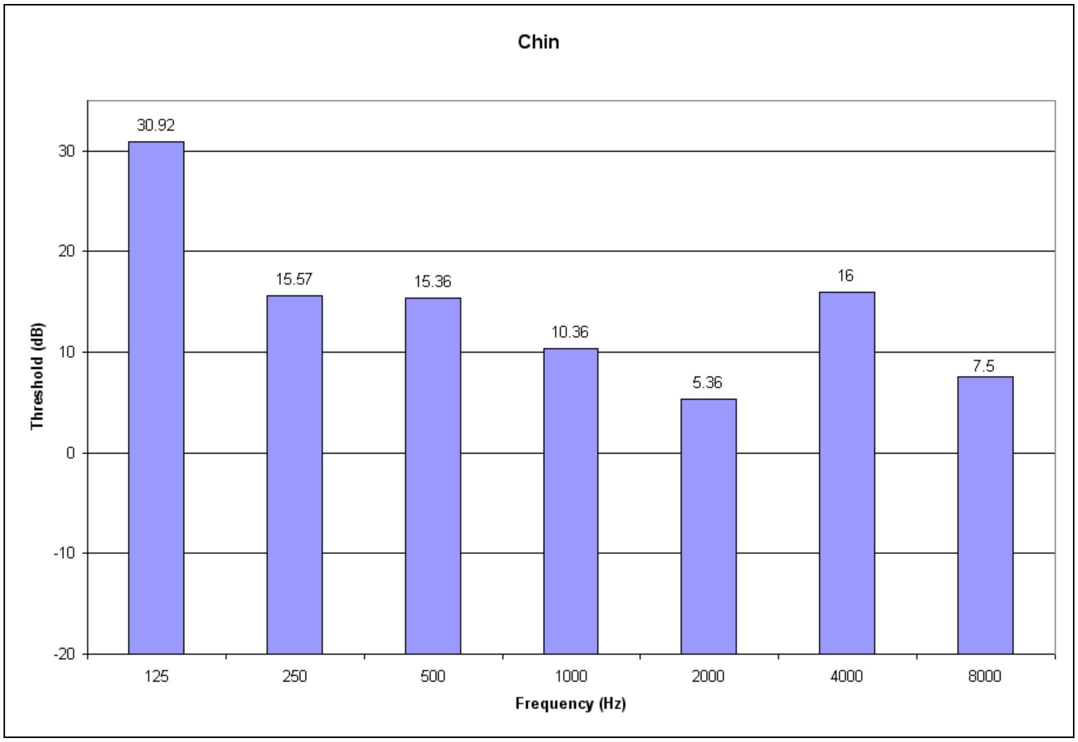

EEE
40
30
20
10
0
-10
-20
-30
Threshold (dB HL)
0.857
-19.29
-1.79
-8.21
-6.07
-12.14
-13.21
-3.21
-7.86
-8.93
-10
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location

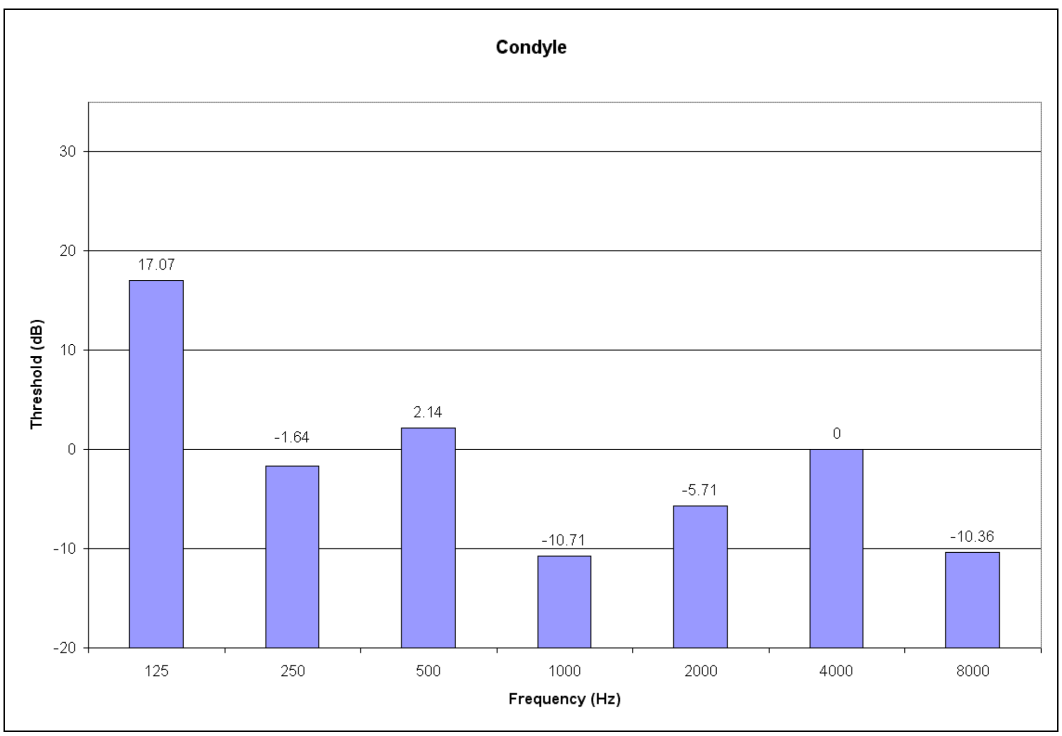

OOH
40
30
20
10
0
-10
-20
-30
Threshold (dB HL)
0.143
-20.36
0.857
-2.36
-5.57
-16.43
-11.07
0
-3.79
-5.36
-12.5
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location

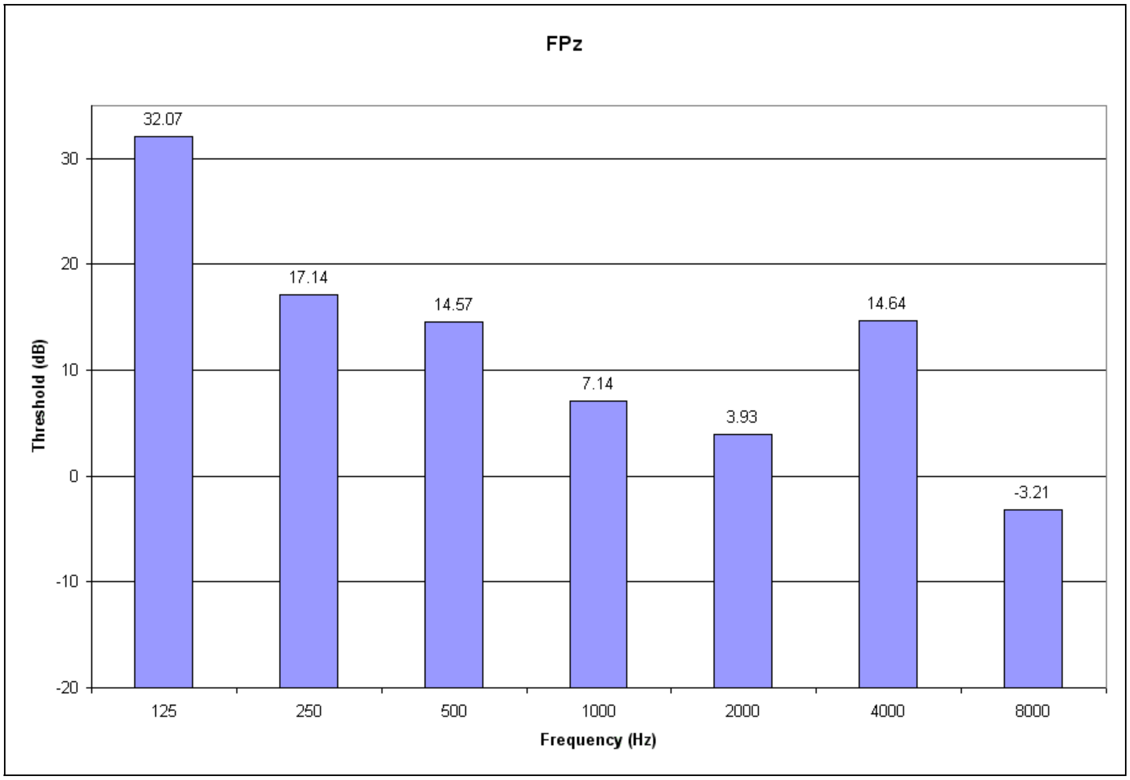

White Noise
Threshold (dB HL)
40
30
20
10
0
-10
-20
-30
3.93
-17.86
-0.714
-5
-6.07
-12.5
-11.79
-0.357
-7.14
-8.93
-10.36
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location

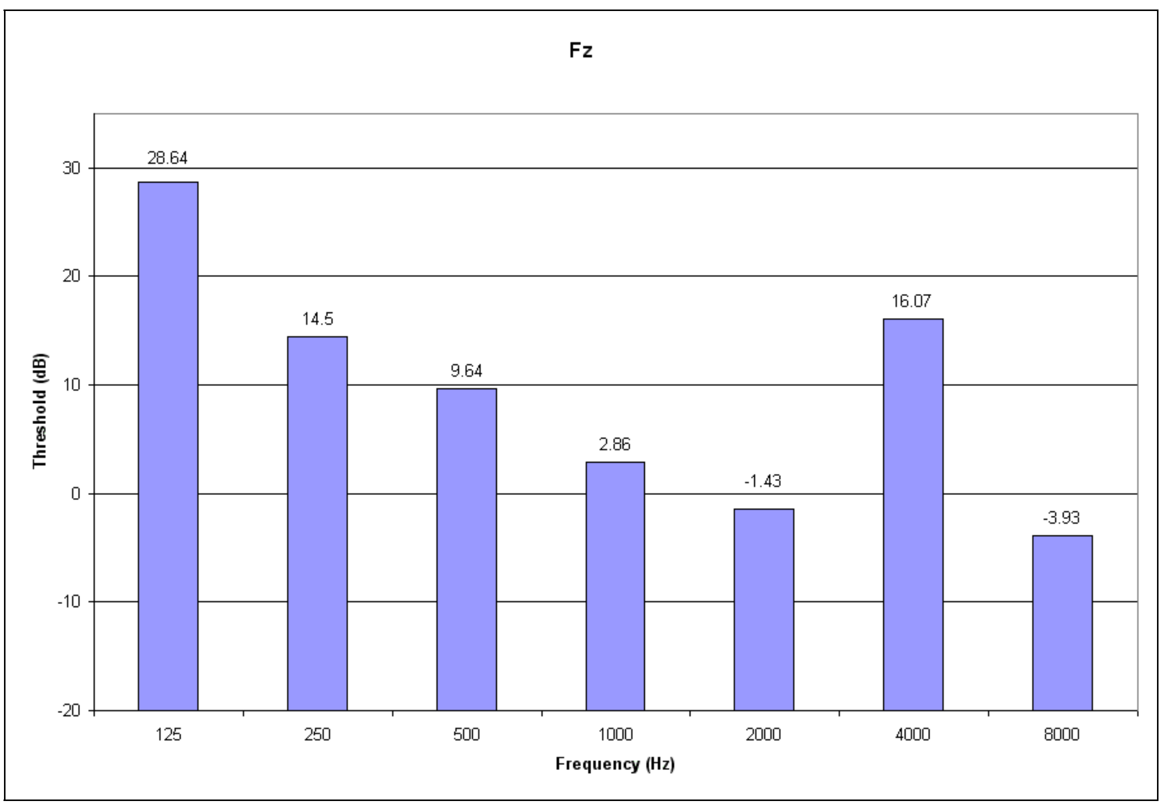

All Signals
Threshold (dB HL)
40
30
20
10
0
-10
-20
-30
8.30
-8.50
6.66
3.25
4.67
-4.28
-3.53
7.40
2.18
1.05
-2.26
Chin
Condyle
FPz
Fz
Inion
Jaw Angle
Mastoid
Pz
T3
Temple
Vertex
Location

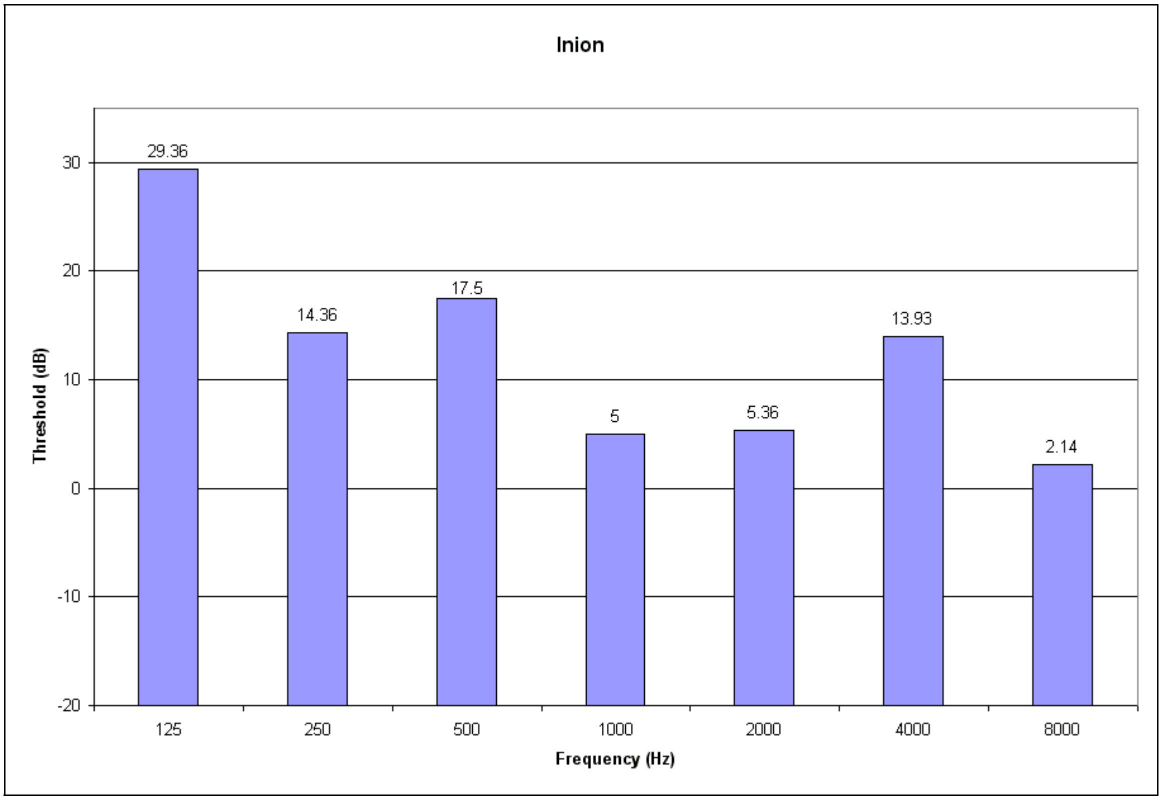
Appendix B. Arithmetic Means of BC Responses Per Location

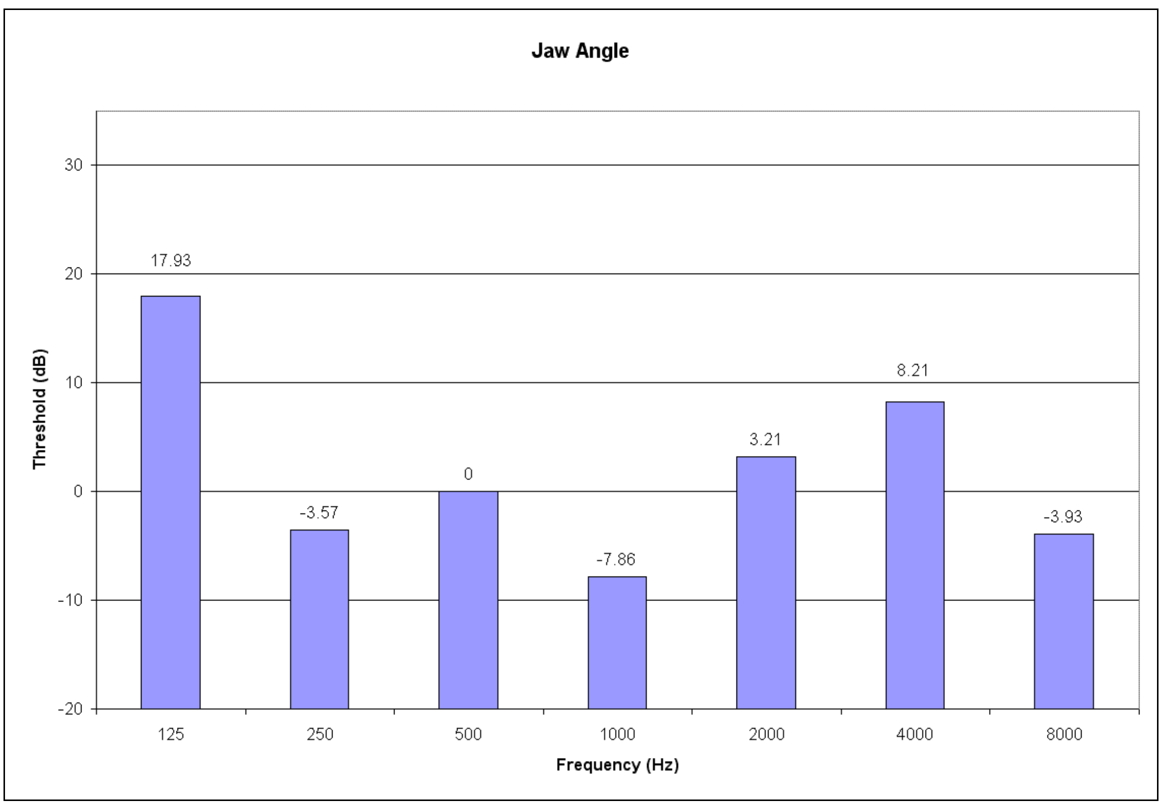


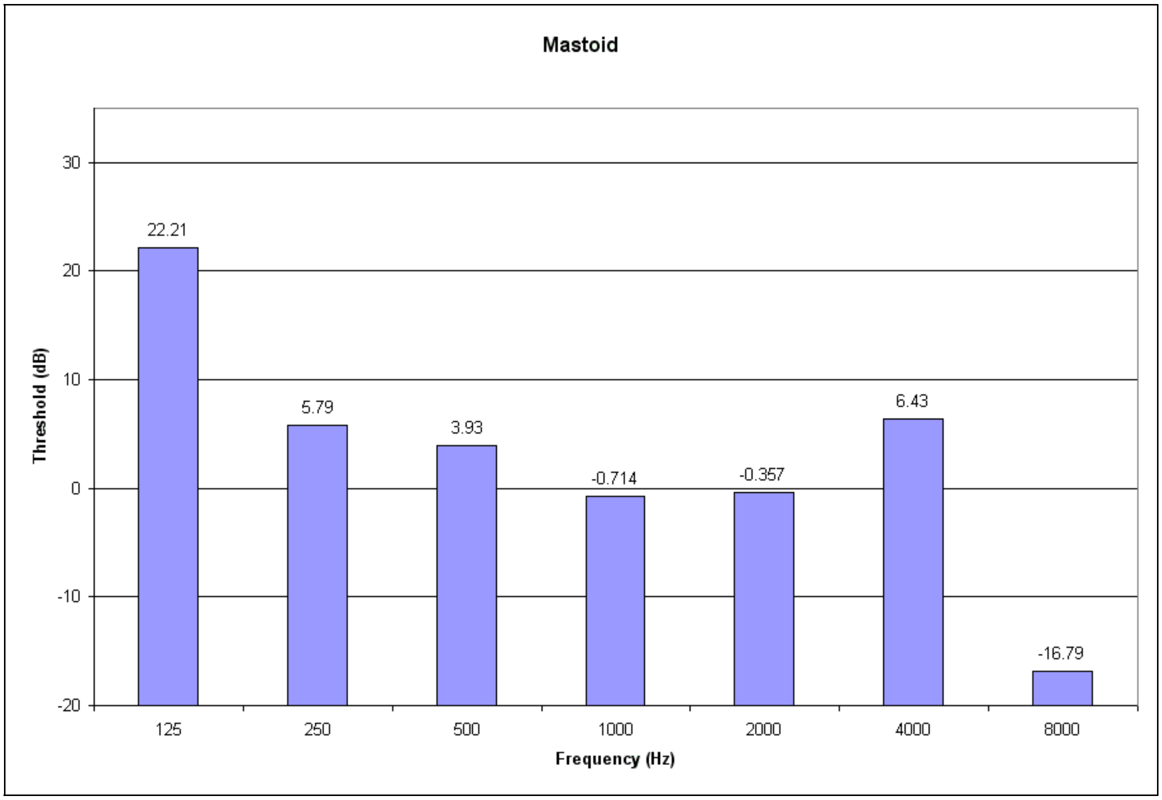


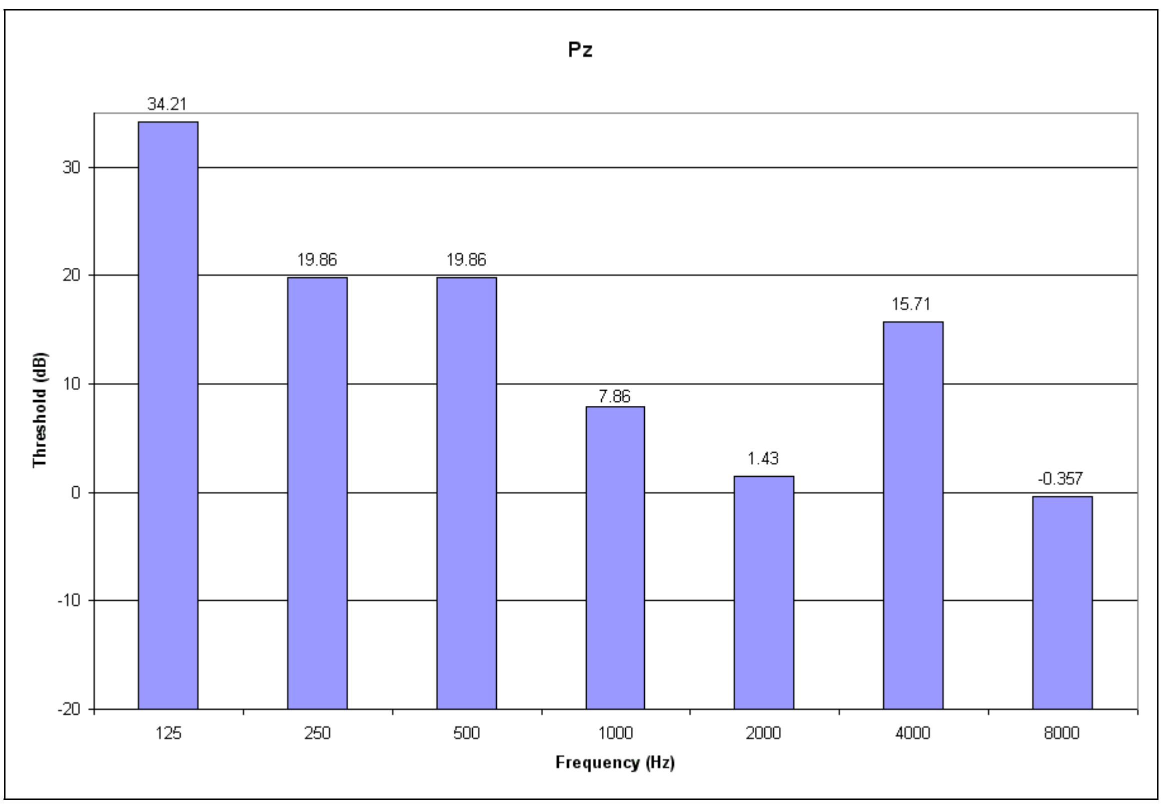

FPz
32.07
17.14
14.57
7.14
3.93
14.64
-3.21
30
20
10
0
-10
-20
Threshold (dB)
125
250
500
1000
2000
4000
8000
Frequency (Hz)

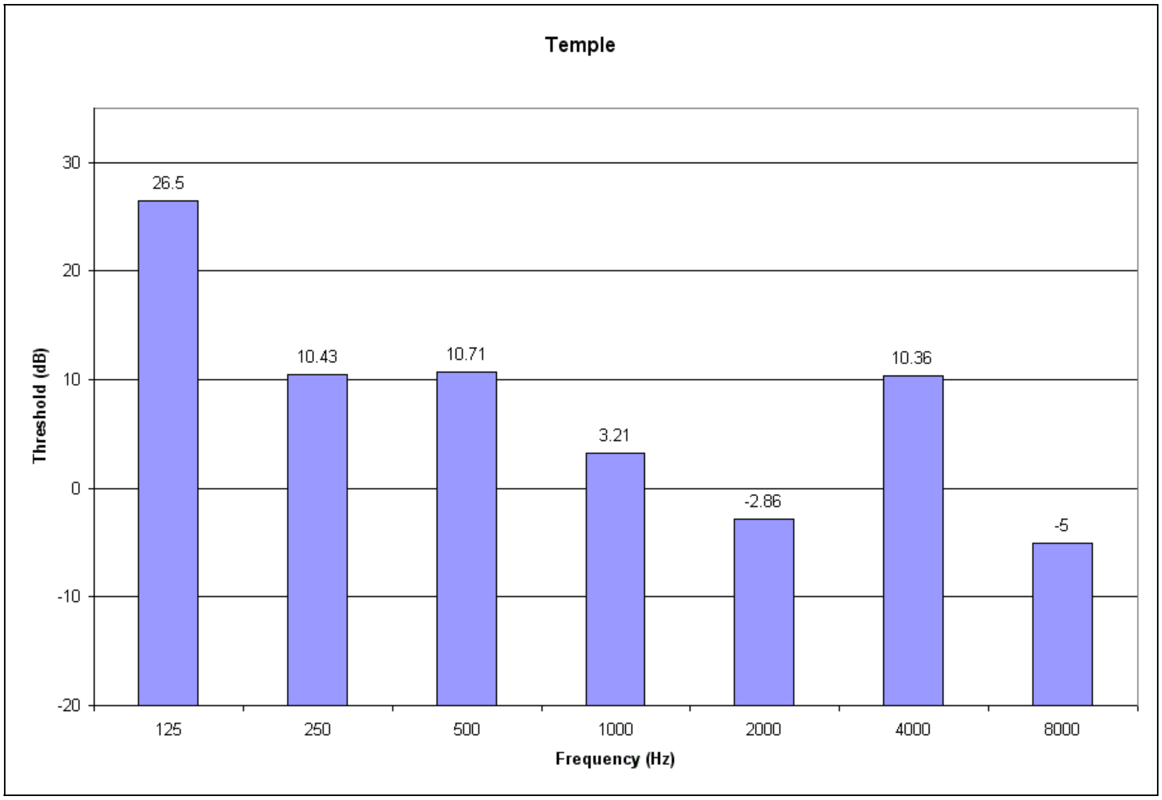

Fz
28.64
14.5
9.64
2.86
-1.43
16.07
-3.93
30
20
10
0
-10
-20
Threshold (dB)
125
250
500
1000
2000
4000
8000
Frequency (Hz)

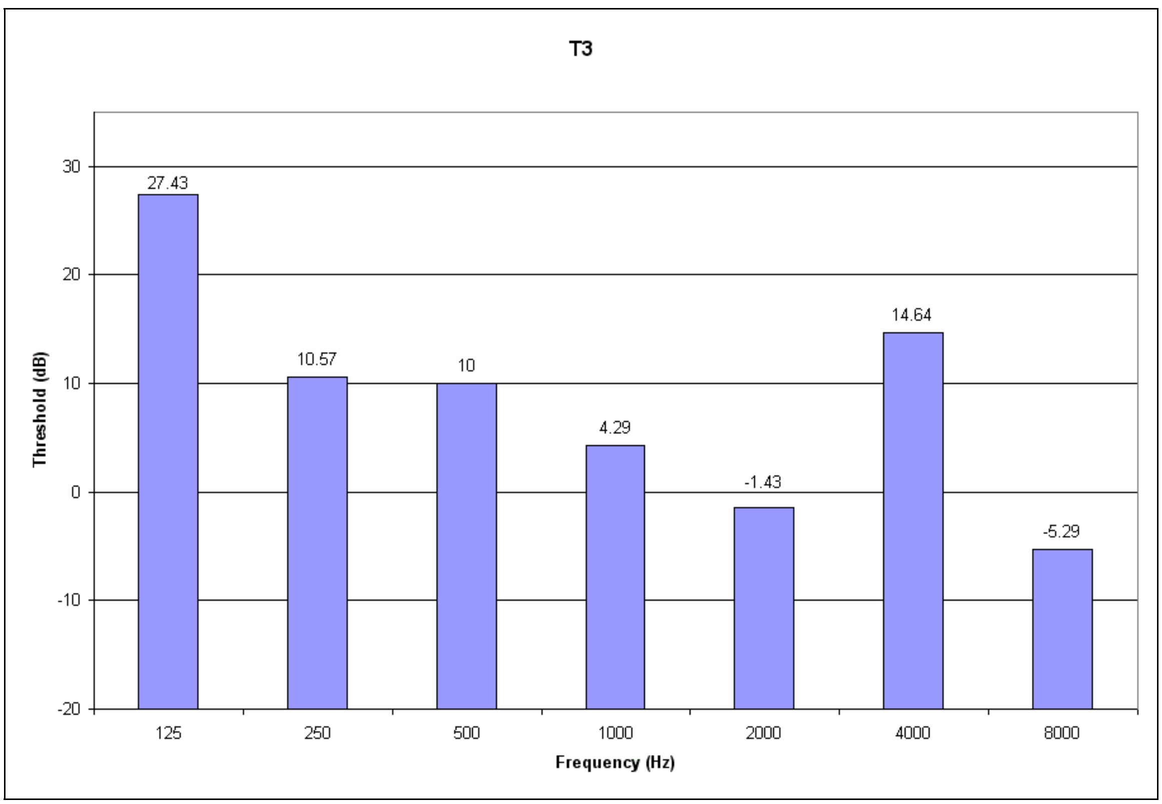

Inion
29.36
14.36
17.5
5
5.36
13.93
2.14
Threshold (dB)
30
20
10
0
-10
-20
125
250
500
1000
2000
4000
8000
Frequency (Hz)

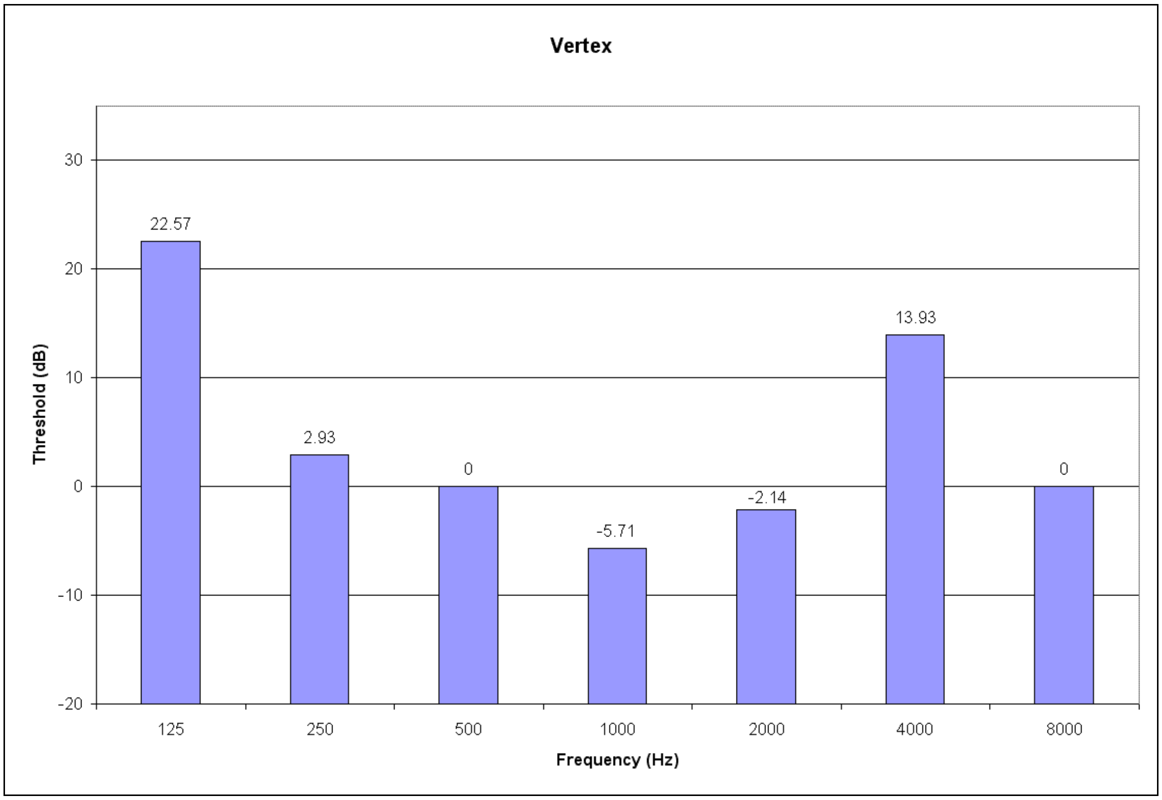

Jaw Angle
17.93
-3.57
0
-7.86
3.21
8.21
-3.93
Threshold (dB)
30
20
10
0
-10
-20
125
250
500
1000
2000
4000
8000
Frequency (Hz)


Mastoid
22.21
5.79
3.93
-0.714
-0.357
6.43
-16.79
30
20
10
0
-10
-20
Threshold (dB)
125
250
500
1000
2000
4000
8000
Frequency (Hz)

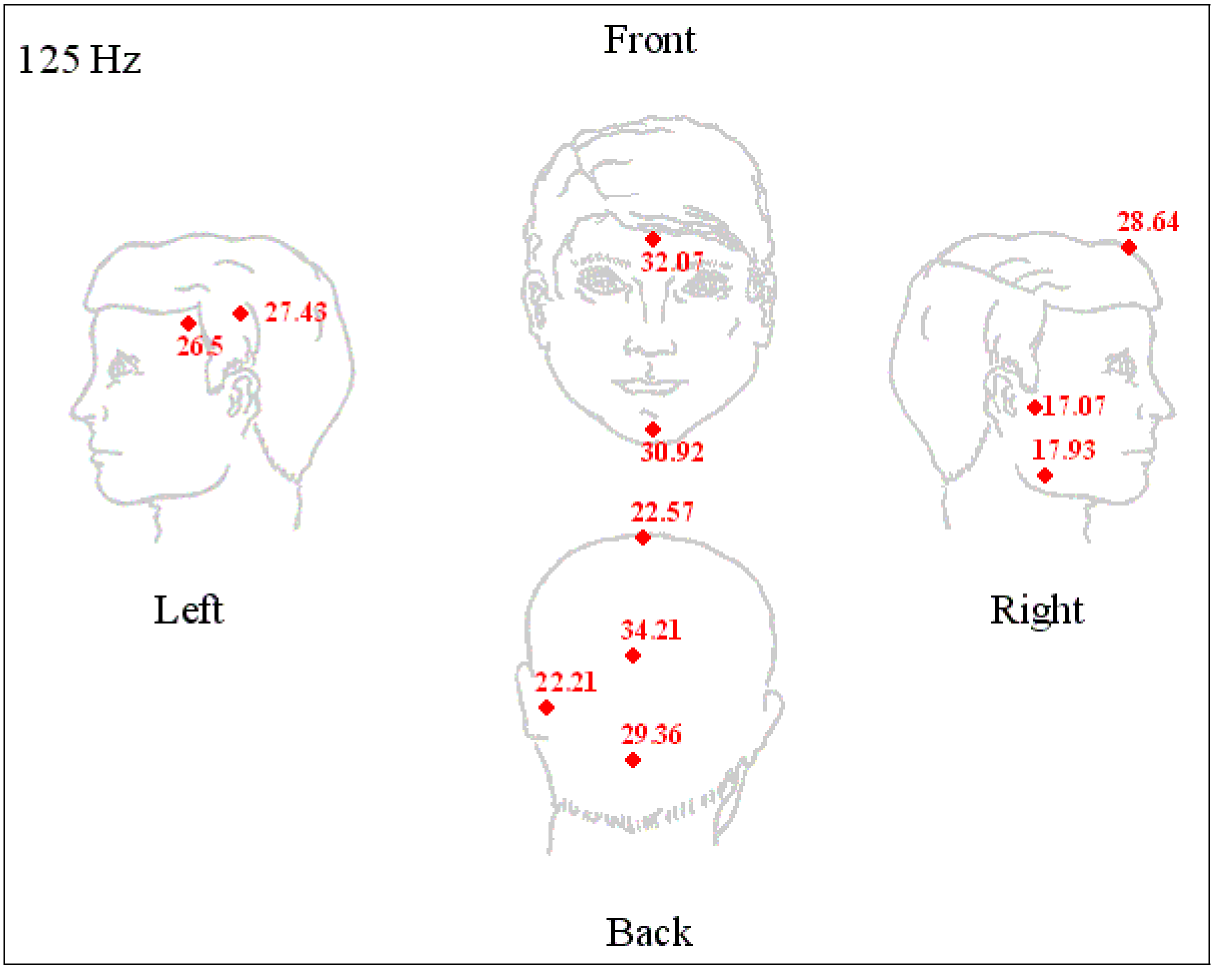

Pz
34.21
19.86
19.86
7.86
1.43
15.71
-0.357
30
20
10
0
-10
-20
Threshold (dB)
125
250
500
1000
2000
4000
8000
Frequency (Hz)

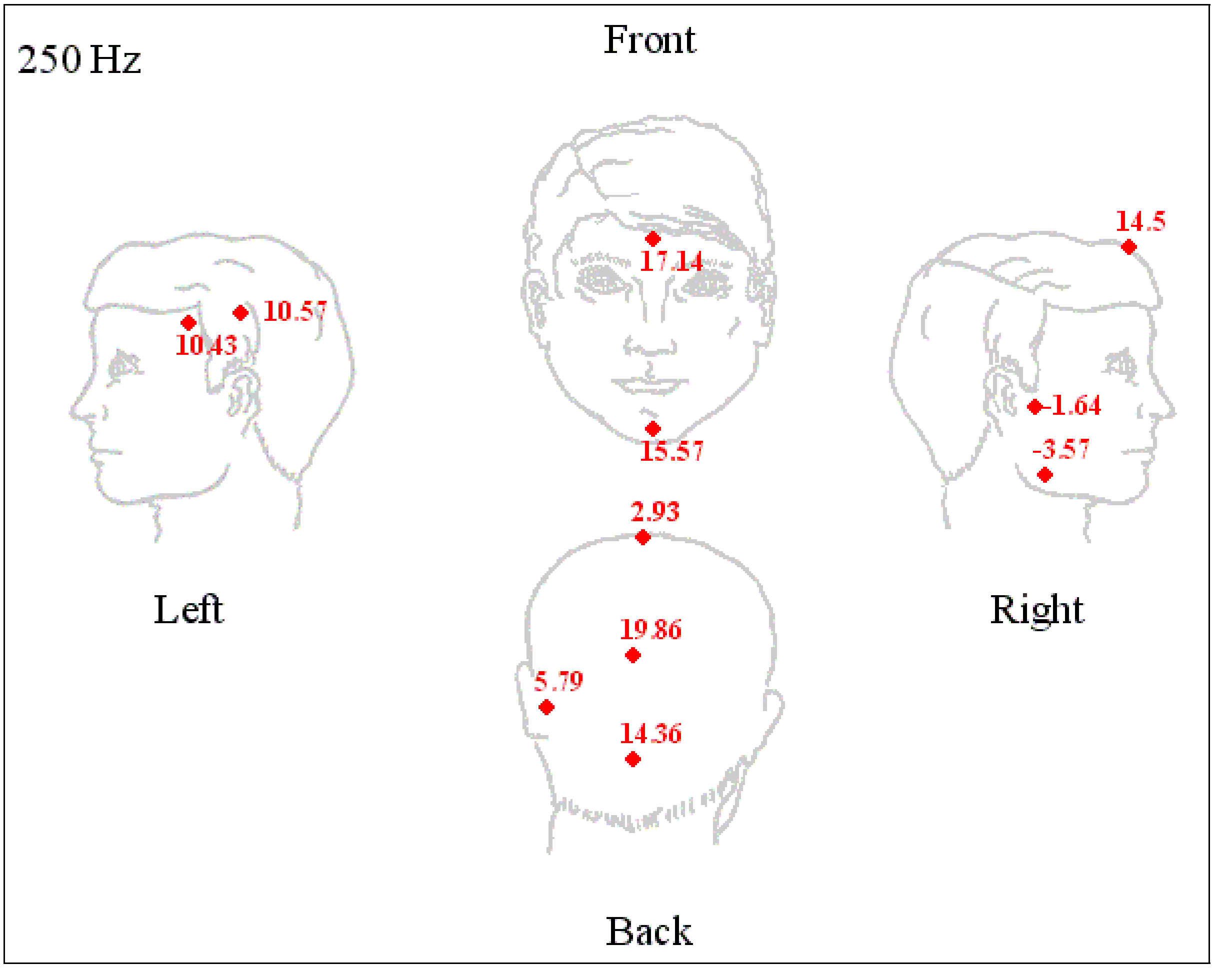

Temple
30
20
10
0
-10
-20
Threshold (dB)
26.5
10.43
10.71
3.21
-2.86
10.36
-5
125
250
500
1000
2000
4000
8000
Frequency (Hz)


T3
30
20
10
0
-10
-20
Threshold (dB)
27.43
10.57
10
4.29
-1.43
14.64
-5.29
125
250
500
1000
2000
4000
8000
Frequency (Hz)

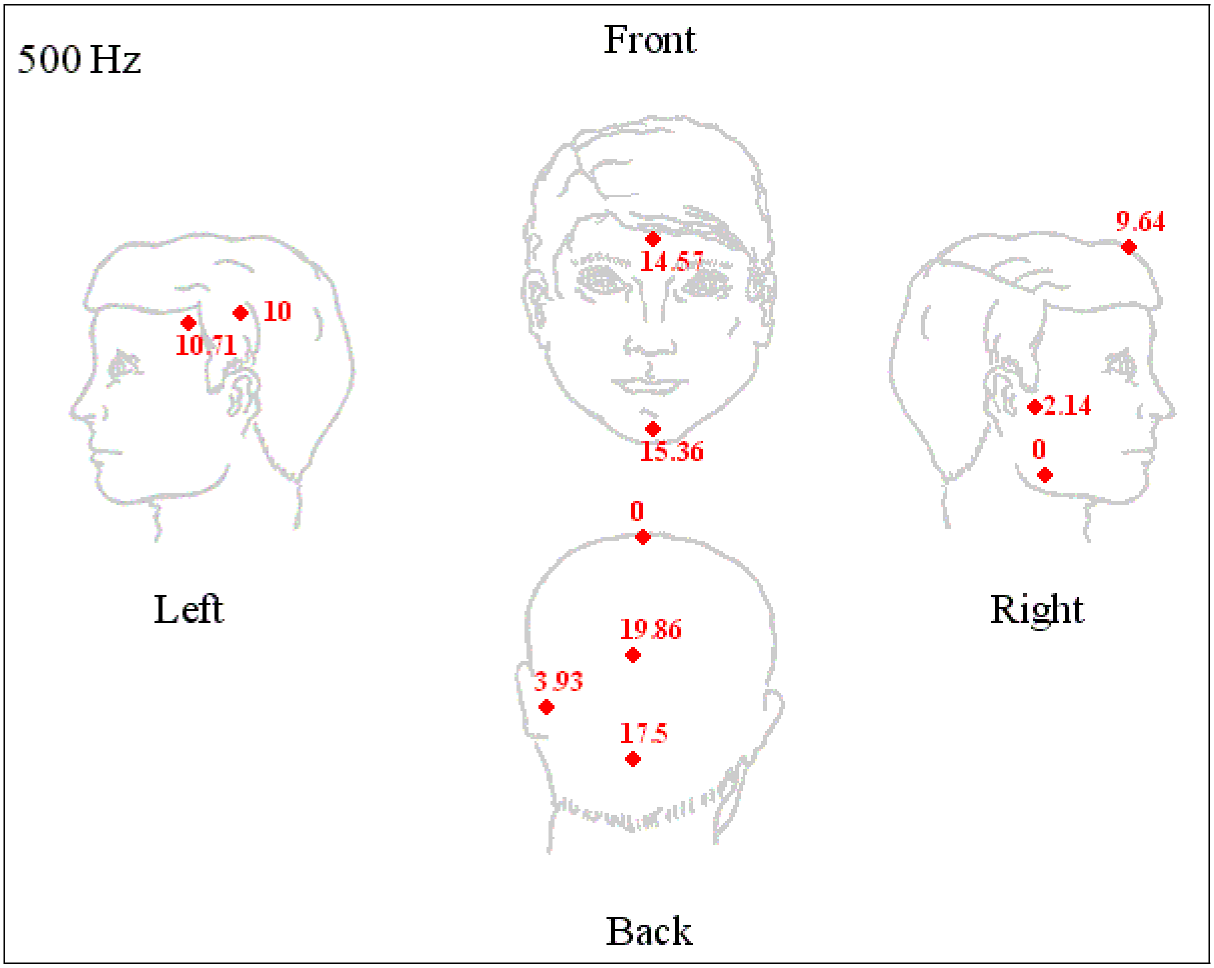

Vertex
Threshold (dB)
30
20
10
0
-10
-20
22.57
2.93
0
-5.71
-2.14
13.93
0
125
250
500
1000
2000
4000
8000
Frequency (Hz)

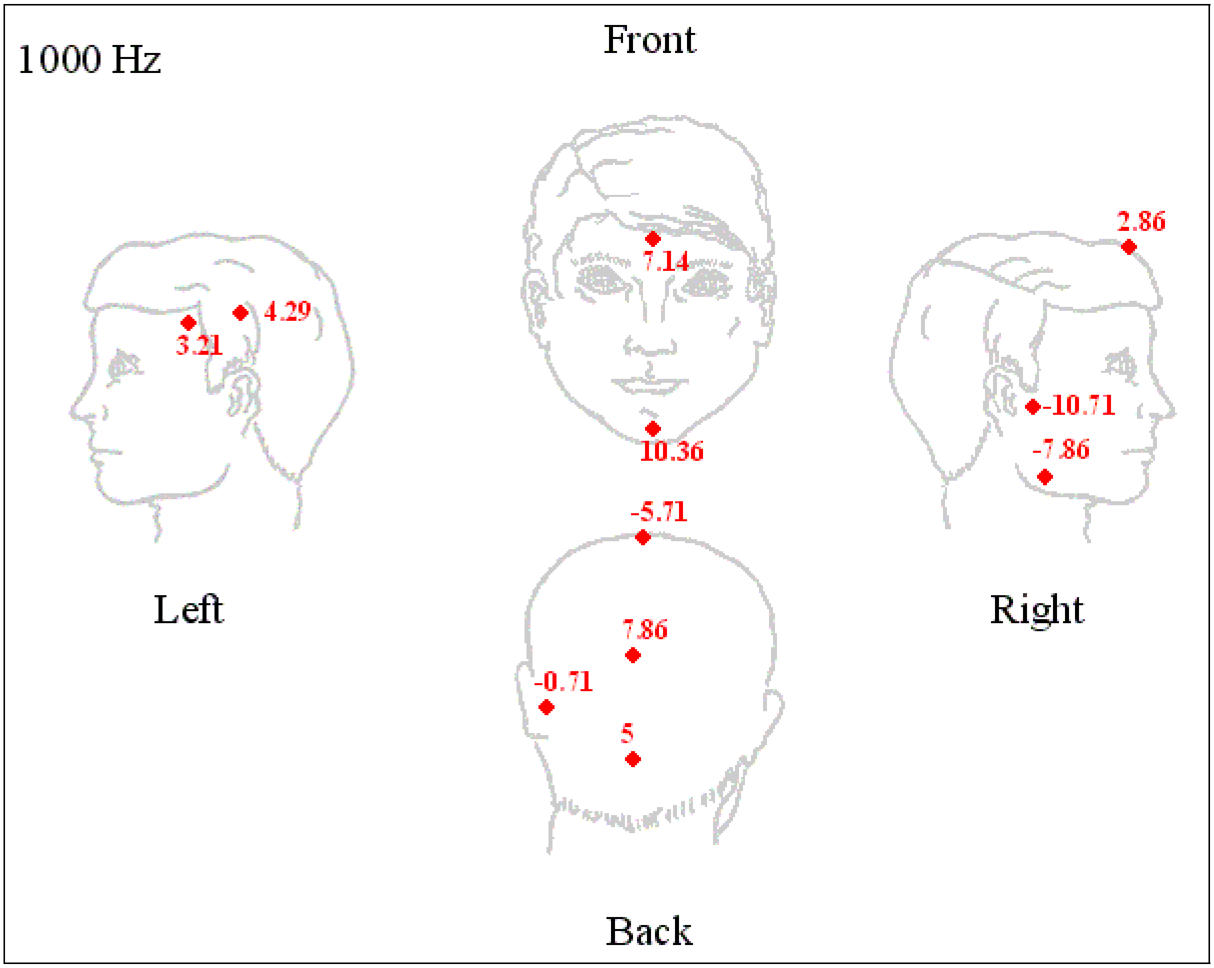
Appendix C. Head Views

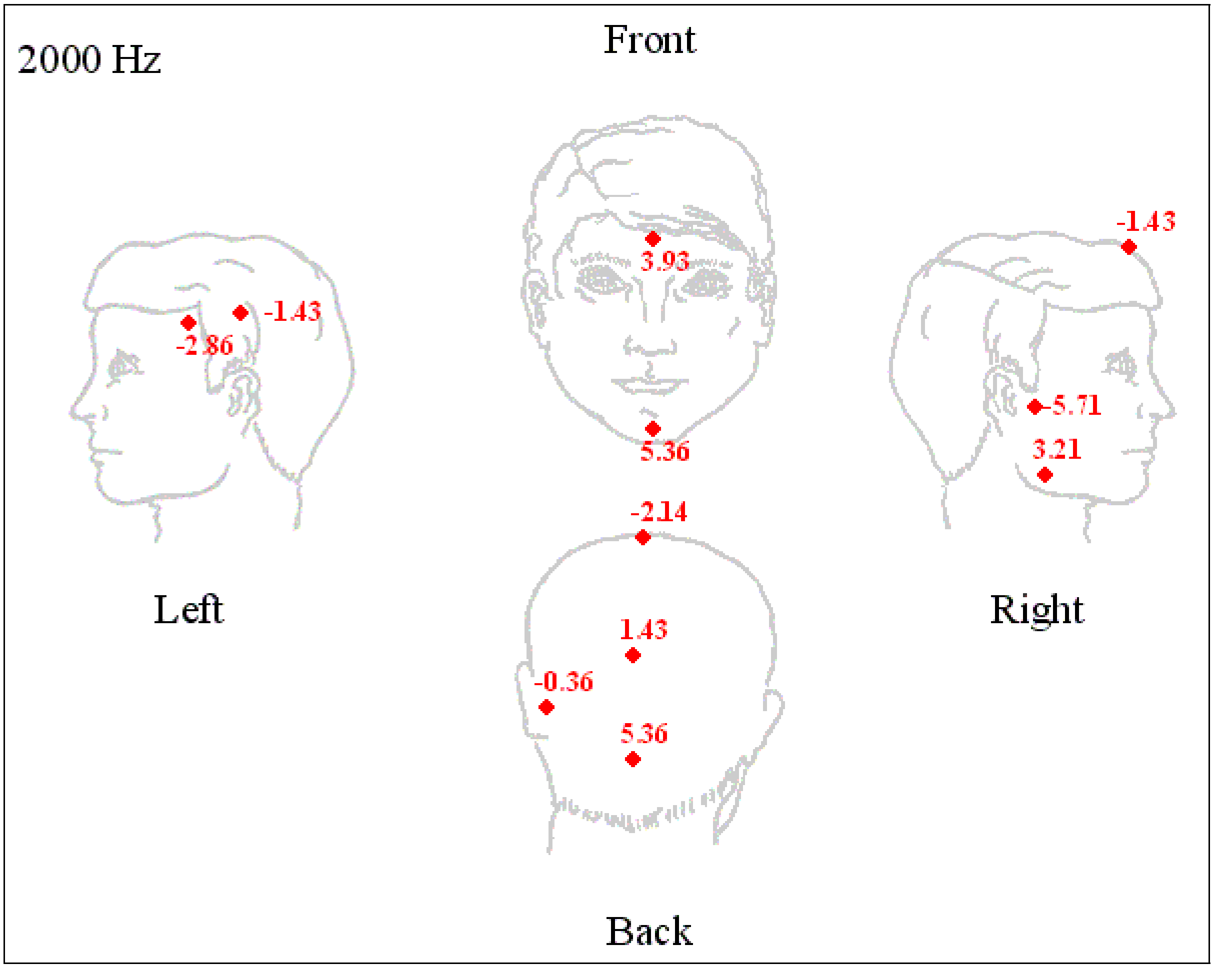


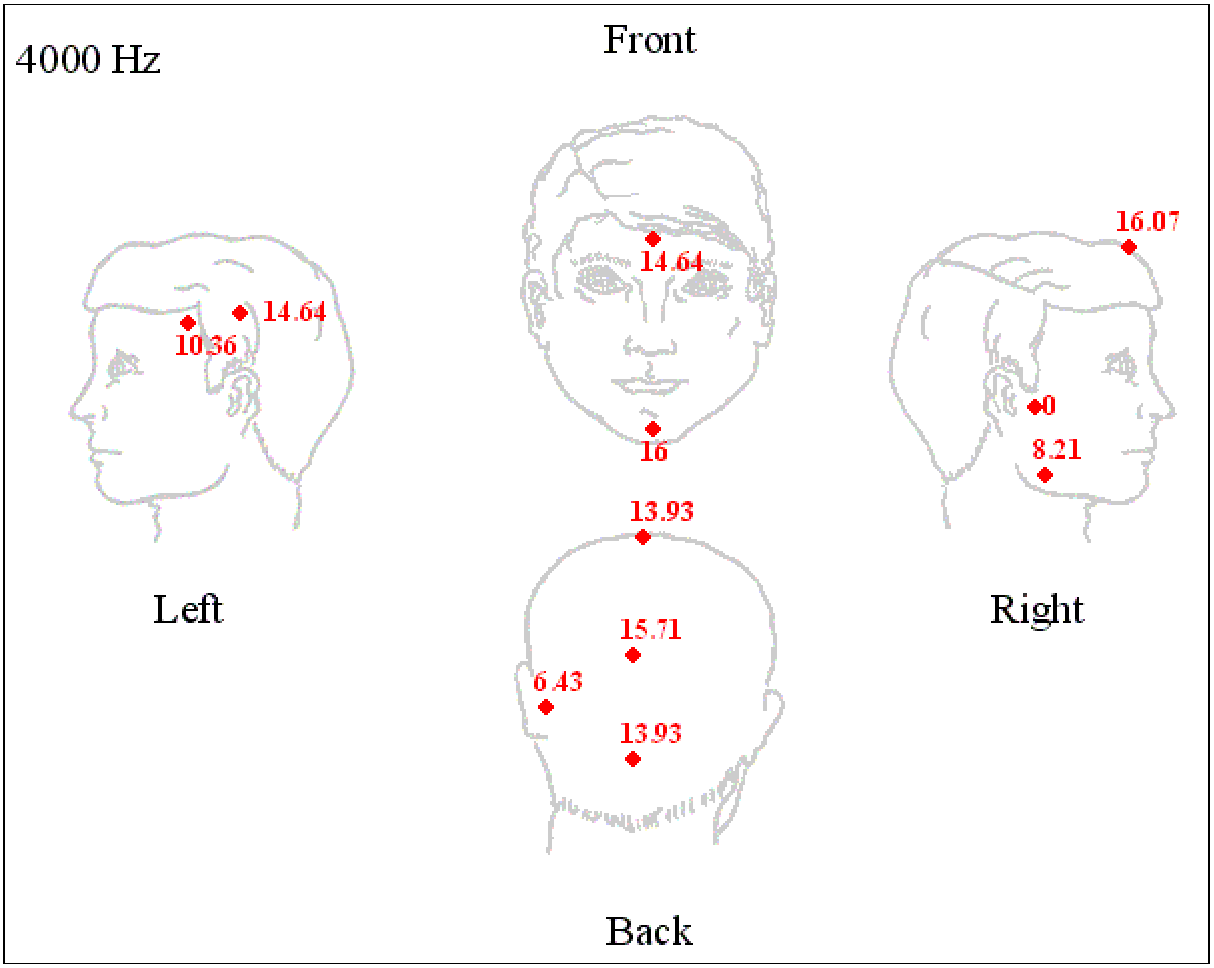


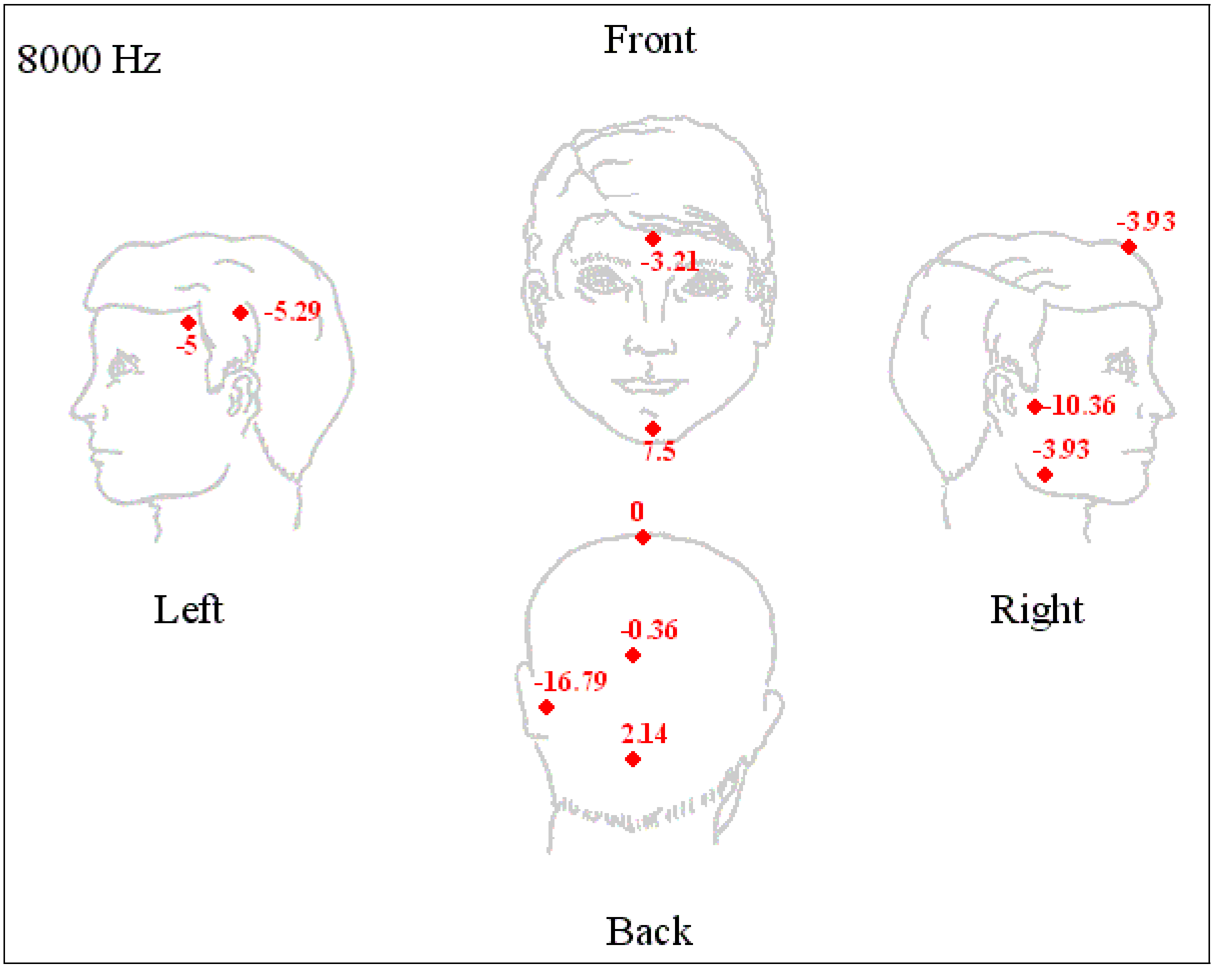
250 Hz
Front
17.14
15.57
10.57
10.43
14.5
-1.64
-3.57
2.93
Left
Right
19.86
5.79
14.36
Back

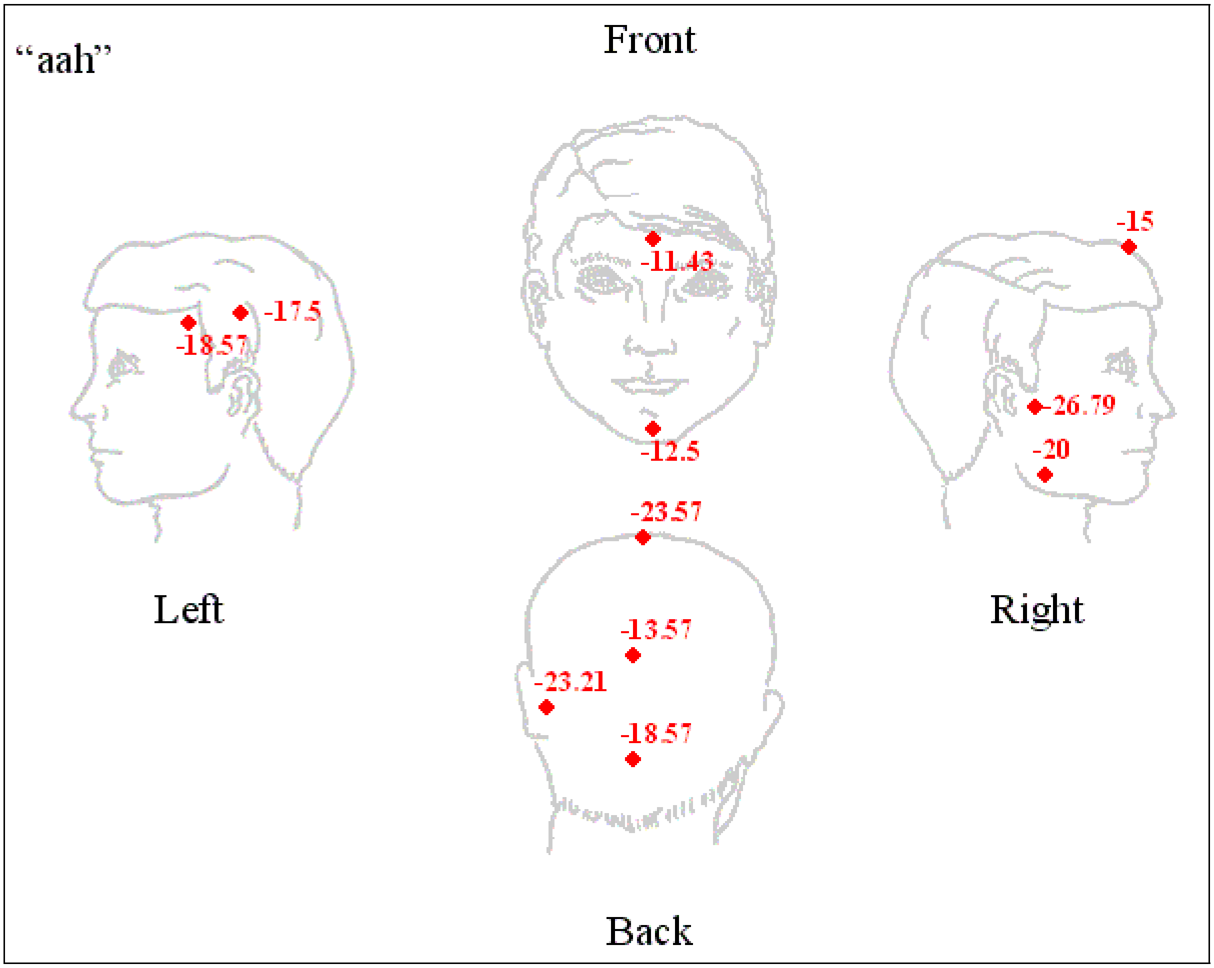

500 Hz
Front
14.57
15.36
10
10.71
9.64
2.14
0
0
19.86
3.93
17.5
Left
Right
Back

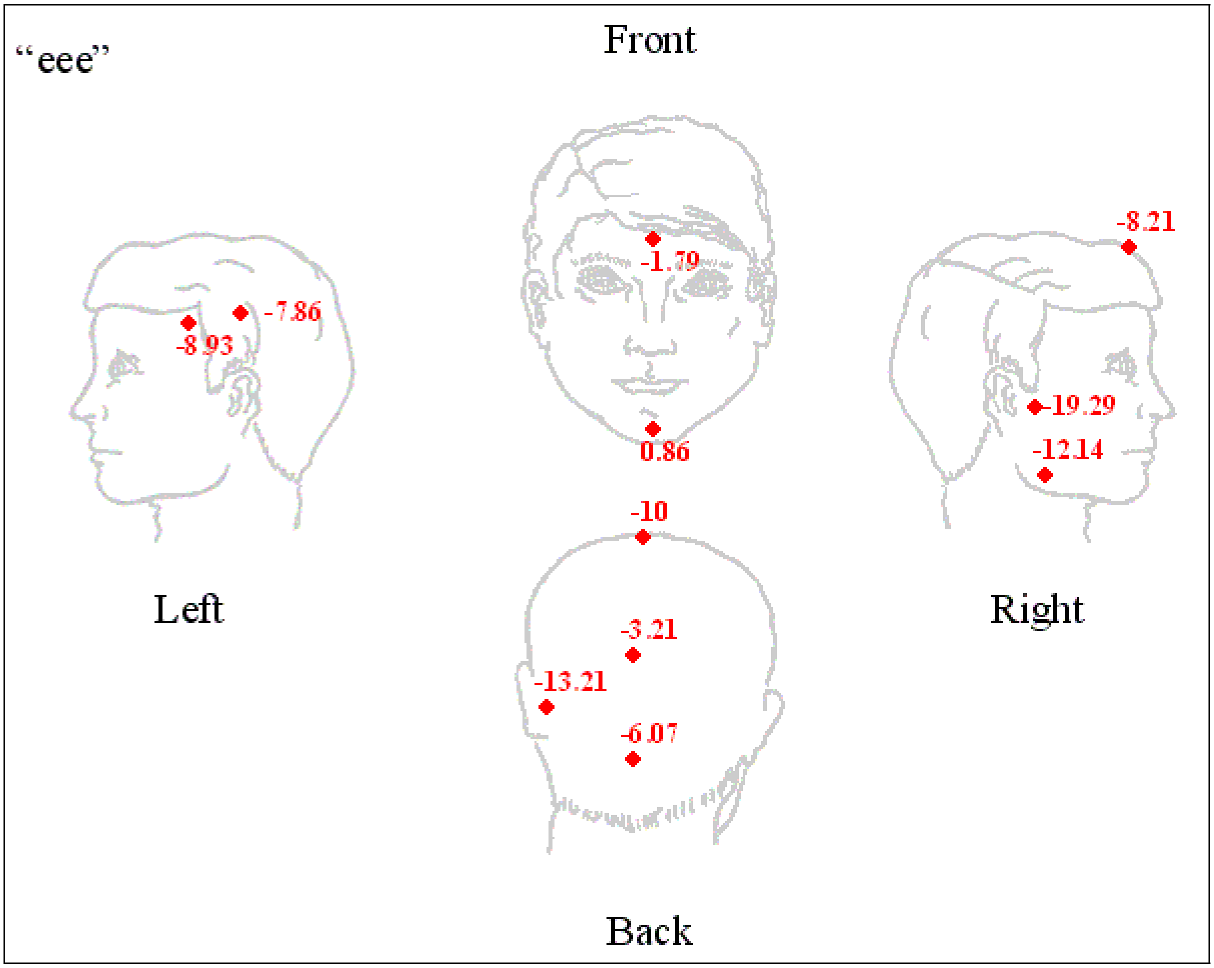

1000 Hz
Front
7.14
10.36
4.29
3.21
2.86
-10.71
-7.86
-5.71
7.86
-0.71
5
Left
Right
Back

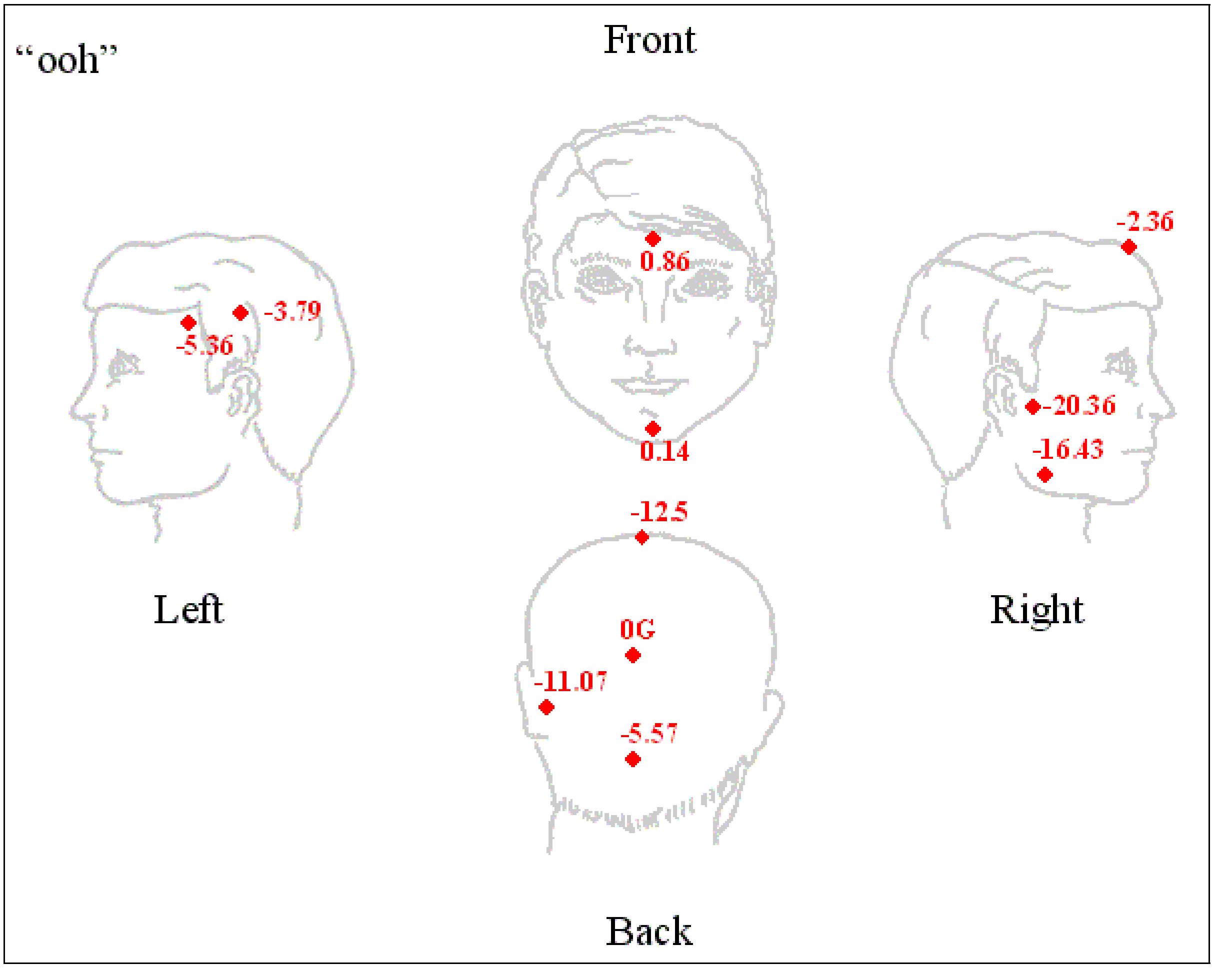

2000 Hz
Front
3.93
5.36
-1.43
-2.86
Left
-1.43
-5.71
3.21
Right
-2.14
1.43
-0.36
5.36
Back

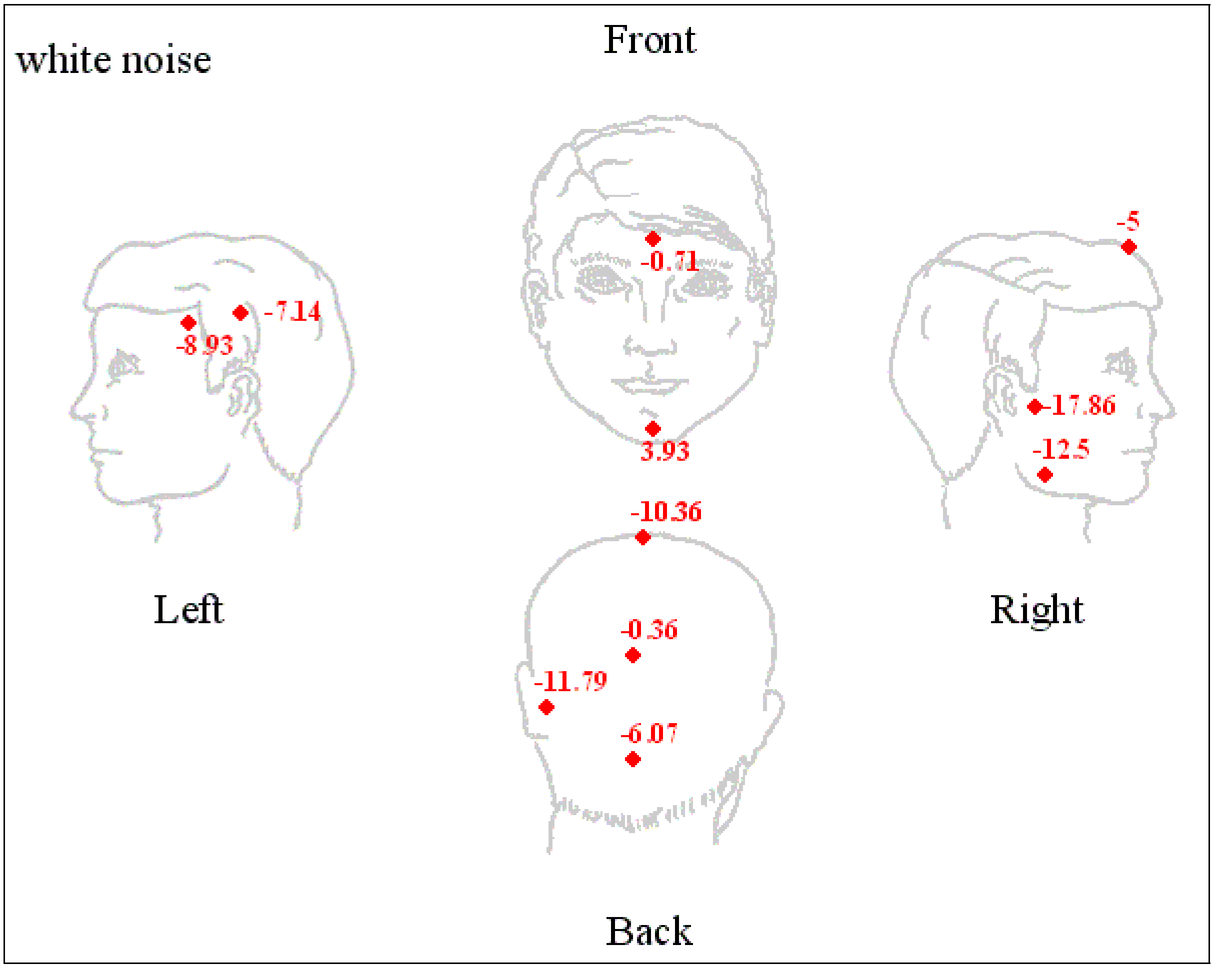

4000 Hz
Front
14.64
16
Left
14.64
10.36
Right
16.07
0
8.21
13.93
15.71
6.43
13.93
Back

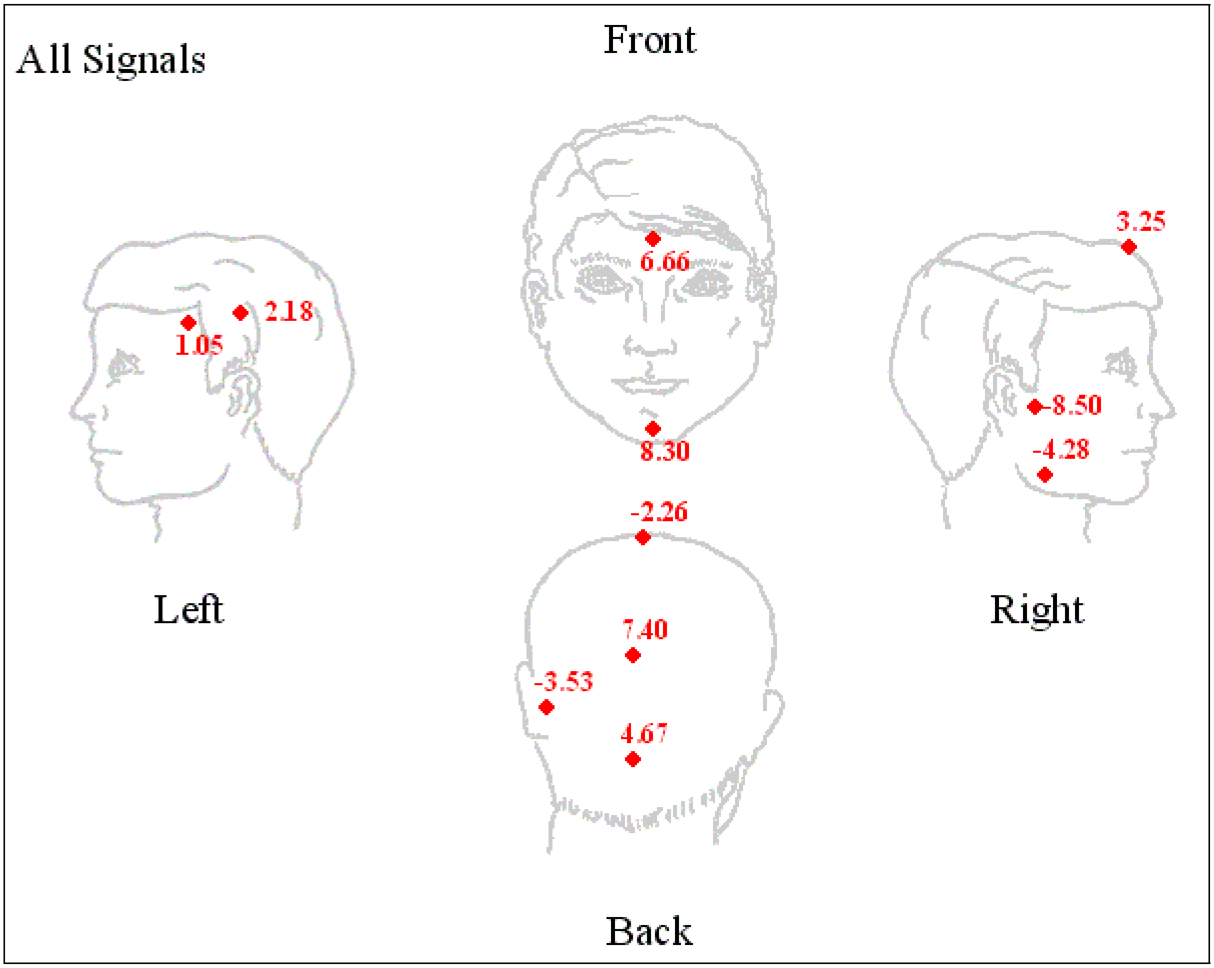

8000 Hz
Front
-3.21
7.5
-5.29
-5
-3.93
-10.36
-3.93
Left
Right
0
-0.36
-16.79
2.14
Back


"aah"
Front
-11.43
-12.5
-17.5
-18.57
-15
-26.79
-20
-23.57
-13.57
-23.21
-18.57
Left
Right
Back


"eee"
Front
-1.79
0.86
-7.86
-8.93
Left
-8.21
-19.29
-12.14
Right
-10
-3.21
-13.21
-6.07
Back


"ooh"
Front
0.86
0.14
-3.79
-5.36
Left
-2.36
-20.36
-16.43
Right
-12.5
0G
-11.07
-5.57
Back


white noise
Front
-0.71
3.93
-7.14
-8.93
-5
-17.86
-12.5
-10.36
-0.36
-11.79
-6.07
Left
Right
Back


All Signals
Front
6.66
8.30
2.18
1.05
3.25
-8.50
-4.28
-2.26
Left
Right
7.40
-3.53
4.67
Back

Appendix D. Location Ranks

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
1	Condyle	Jaw Angle	Jaw Angle	Condyle	Condyle	Condyle	Mastoid
2	Jaw Angle	Condyle	Vertex	Jaw Angle	Temple	Mastoid	Condyle
3	Mastoid	Vertex	Condyle	Vertex	Vertex	Jaw Angle	T3
4	Vertex	Mastoid	Mastoid	Mastoid	Fz	Temple	Temple
5	Temple	Temple	Fz	Fz	T3	Vertex	Fz
6	T3	T3	T3	Temple	Mastoid	Inion	Jaw Angle
7	Fz	Inion	Temple	T3	Pz	FPz	FPz
8	Inion	Fz	FPz	Inion	Jaw Angle	T3	Pz
9	Chin	Chin	Chin	FPz	FPz	Pz	Vertex
10	FPz	FPz	Inion	Pz	Chin	Chin	Inion
11	Pz	Pz	Pz	Chin	Inion	Fz	Chin

	aah	eee	ooh	white
1	Condyle	Condyle	Condyle	Condyle
2	Vertex	Mastoid	Jaw Angle	Jaw Angle
3	Mastoid	Jaw Angle	Vertex	Mastoid
4	Jaw Angle	Vertex	Mastoid	Vertex
5	Inion	Temple	Inion	Temple
6	Temple	Fz	Temple	T3
7	T3	T3	T3	Inion
8	Fz	Inion	Fz	Fz
9	Pz	Pz	Pz	FPz
10	Chin	FPz	Chin	Pz
11	FPz	Chin	FPz	Chin

Rank ave			Sorted by rank ave		
A	Chin	10	B	Condyle	1.4
B	Condyle	1.4	G	Mastoid	3.3
C	FPz	9.2	F	Jaw Angle	3.5
D	Fz	6.8	K	Vertex	3.8
E	Inion	7.9	I	Temple	5.2
F	Jaw Angle	3.5	J	T3	6.2
G	Mastoid	3.3	D	Fz	6.8
H	Pz	9.5	E	Inion	7.9
I	Temple	5.2	C	FPz	9.2
J	T3	6.2	H	Pz	9.5
K	Vertex	3.8	A	Chin	10

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